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AFRPL-TR-69-141

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SUPPLEMENTAL REPORT

WIDE RANGE FLOW CONTROL PROGRAM

F. Merritt
L. Dumont

et al

Technical Report AFRPL-TR-69-141
May 1969

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FOREWORD

This report supplements Technical Report AFRPL-TR-68-32 dated December 1968 and provides additional liquid hydrogen flow test data for a caviatating venturi throttle valve. The study and test program was conducted by TRW Systems in fulfillment of the requirement of U. S. Air Force Contract AF04(611)-10819, Project Number 3058 and Task Number 305802 entitled, "Wide Range Flow Control." Air Force Project Engineers during the course of the program were Mr. James R. Lawrence and Mr. Jack Hartley/RPRPD. The TRW Project Engineer was Mr. F. L. Merritt.

The program was initiated in June 1965 as a continuation of effort under Contract AF04(611)-9100 entitled, "Investigation of New Concepts for a Propellant Feed System Component," Report AFRPL-TR-65-130. This previous program was carried out over the period 10 June 1963 to 31 January 1965.

The liquid hydrogen tests described in this report were conducted for TRW Systems by Wyle Laboratories, Norco, California. Acknowledgment is given to H. R. Wheelock, and other members of the staff of Wyle Laboratories for their efforts in achieving a successful test series. Mr. F. E. Robinett at the TRW Capistrano Test Site provided assistance in water flow testing.

This report was submitted for approval in April 1969. This technical report has been reviewed and is approved.

Jack Hartley
Project Engineer (RPRPD)

ABSTRACT

The objective of the Wide Range Flow Control Program was to establish propellant flow control valve technology including techniques for mixture ratio control for deep throttling of liquid fluorine-liquid hydrogen rocket engine systems for rated thrust levels between 15 and 45K. The effort described in this supplemental report met the specific objective of proving the technique of controlling the flow of liquid hydrogen by means of a cavitating venturi control valve. Typical inlet conditions for the hydrogen during the tests were a pressure of 465 ±10 psia and a temperature of 40° to 45°R. The design mass flow rate at the 100 percent throttle setting was 2.88 lb/sec. Although the hydrogen flow stream was at a supercritical pressure it was demonstrated to act as a subcritical cavitating liquid at the low static pressures prevailing in the valve throat. The feasibility of control was demonstrated over a flow range in excess of 50 to 1 with valve overall differential pressures from 20 to 400 psid. A recovery of 92 percent on the cavitation line at full throttle position was observed. A discharge coefficient of 0.9 from 2 to 10 percent and 0.875 from 20 percent through 110 percent was calculated from the data.

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SECTION I

INTRODUCTION

This report supplements the Wide Range Flow Control Program Final Report, Reference 1. The effort described involves water and liquid hydrogen flow tests of a variable area cavitating throttle valve. The tests constitute a final effort in the program which was vital to establishing the feasibility of application of the cavitating venturi principle to control of liquid hydrogen. The tests are a continuation of the work described in Section VII of Reference 1. The liquid hydrogen flow tests were conducted by Wyle Laboratories at their Norco facility. The design of the test valve is described in the report (Reference 1). Modifications made for this test series are described in Section III of this report.

1.1 TEST OBJECTIVES

The specific objectives of the flow test effort were:

- To prove the feasibility of the cavitating venturi for control of liquid hydrogen at supercritical inlet pressure conditions.
- To demonstrate achievable accuracies.
- To observe differences between predicted and test parameters.
- To provide engineering data for discharge coefficient, recovery pintle contour characteristics, and vibration characteristics as available.

The theoretical flow process from a thermodynamic standpoint is illustrated by the portion of the temperature-entropy diagram for parahydrogen shown in Figure 1. As discussed in Section III of Reference 1, the acceleration process from the valve inlet to the throat is essentially a reversible adiabatic or isentropic process which can be represented by a vertical line on the diagram. The range shown by the vertical process lines covers the design inlet temperature excursion of 37° to 60°R with the nominal shown by the middle line at 51°R. Vapor pressure at the liquid line for the corresponding temperature represents the predicted throat pressure when in cavitation as a liquid. The test was planned to demonstrate the control capability when operating at points within the range.

To relate the flow results to geometric accuracy of the valve, pintle measurements were made and provided as part of the test information. Flow test results are plotted on the predicted flow diagrams to clarify the differences obtained.

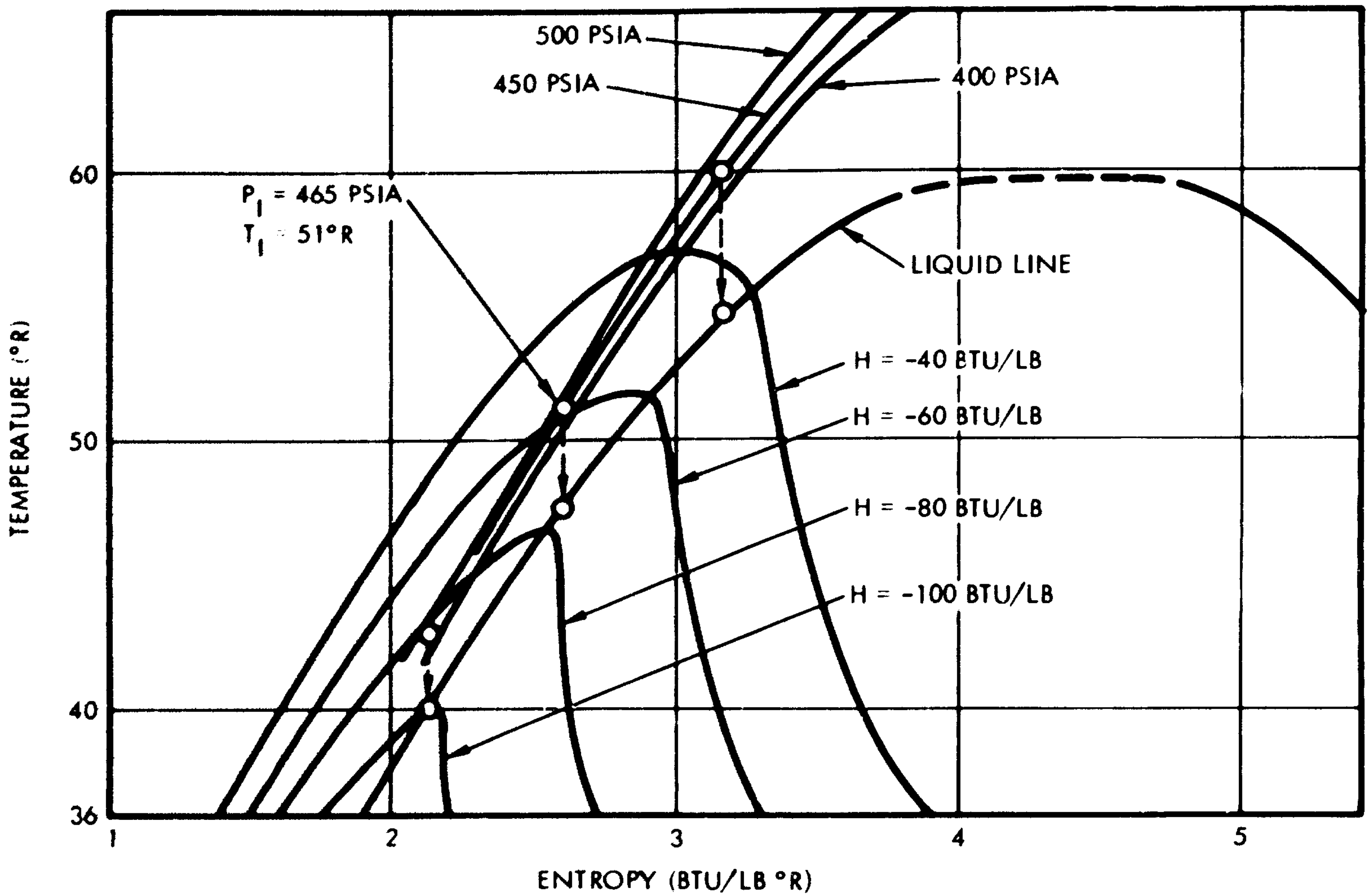


Figure 1. Liquid Hydrogen Flow Process in Cavitating Valve

1.2 TEST APPROACH

In order to provide flow data for the valve based upon more predictable flow of a noncompressible liquid, the valve was initially evaluated and final calibration before hydrogen test was established by water test. Proper function was thereby assured before committing the valve to the hydrogen testing. Modifications to improve bearing reliability and to reduce a vibrational instability to acceptable levels were necessary as part of this effort.

SECTION II

SUMMARY

The test objectives established for the liquid hydrogen test series were all met. The feasibility of control of liquid hydrogen at the supercritical inlet pressure of 465 psia by means of the cavitating venturi principle was established. The potential achievable accuracy was demonstrated in that the pintle contour inaccuracy of the test valve was in the order of ±0.1 percent while test instrument errors are at least an order of magnitude greater.

The differences between the predicted and observed flow rates in cavitation provided useful design data. The flow coefficient of 0.9 proved to be accurate for the flows from 2 through 10 percent. From 20 through 110 percent a very nearly constant coefficient of 0.875 was apparent. To provide a more accurately linear valve, the pintle contour should be recalculated on the basis of the revised values. The cavitation line proved to be at lower differential pressure than predicted over most of the throttle range. A constant recovery of 92 percent was apparent from 20 to 100 percent flow.

Pintle vibration initially observed in early water tests of the valve was virtually eliminated by installation of an additional support immediately upstream of the throat. Only an intermittent vibration at throttle settings up to 7 percent at frequencies in the order of 1700 to 1900 Hz remained. Flows appeared to be unchanged whether in or out of vibration.

SECTION III

TEST COMPONENT DESIGN

The design principles applied to the liquid hydrogen cavitating valve configuration were initially discussed in Reference 2 and in Section I of the Final Report (Reference 1). Detailed design of the valve was described in Section V of Reference 1. Modification of both internal details and instalation of the valve were required for completion of the test program described here. The basic cross section of the valve and installation design are shown in Figure 2. External views of the valve are shown in Figure 3 (see Test Section, Figure 10). The disassembled valve and internal details are shown in Figures 4, 5, and 6.

3.1 DESIGN CONCEPTS

The internal detailed design was predicated on the objectives of attaining flow accuracy over a 50 to 1 linear range of ±1 percent and maximum recovery on the cavitation line at the higher throttle settings. The greatest uncertainty in calculating the throat areas required to achieve a given flow parameter with respect to valve stroke is estimating the discharge coefficient C_D. For purposes of the present design, a coefficient of 0.90 was assumed throughout the flow range based upon experience obtained with the original liquid-fluorine valve tested in the program.

The basis for the throat area determination for liquid hydrogen is the equation for a compressible liquid flowing in a cavitating mode:

$$A = \frac{\dot{W}}{C_d \rho \sqrt{2g\, J\, (H_1 - H_v)}}$$

Where:

A = throat area

C_d = flow coefficient

H_1 = enthalpy at valve inlet

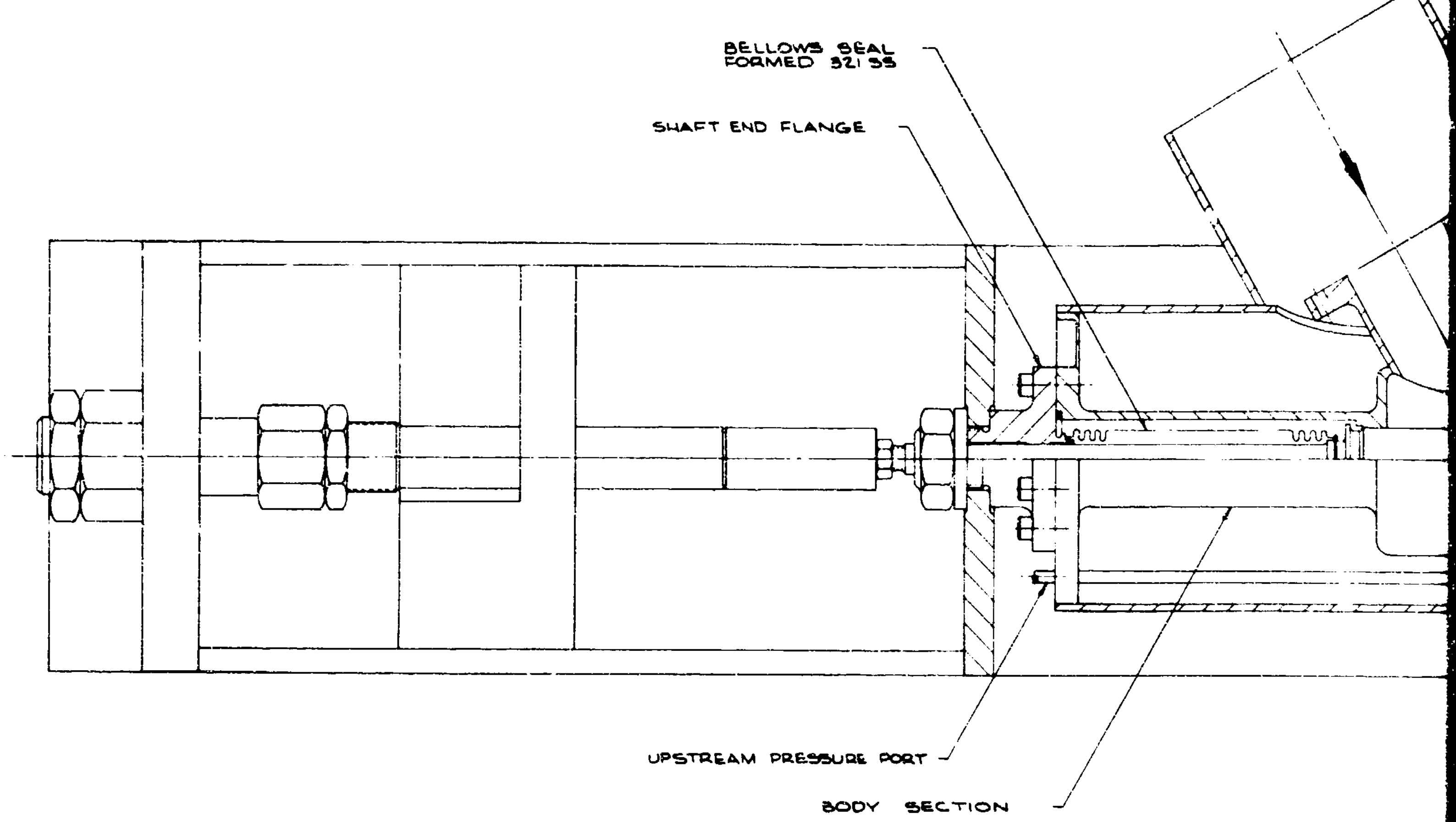
H_v = enthalpy at vapor pressure

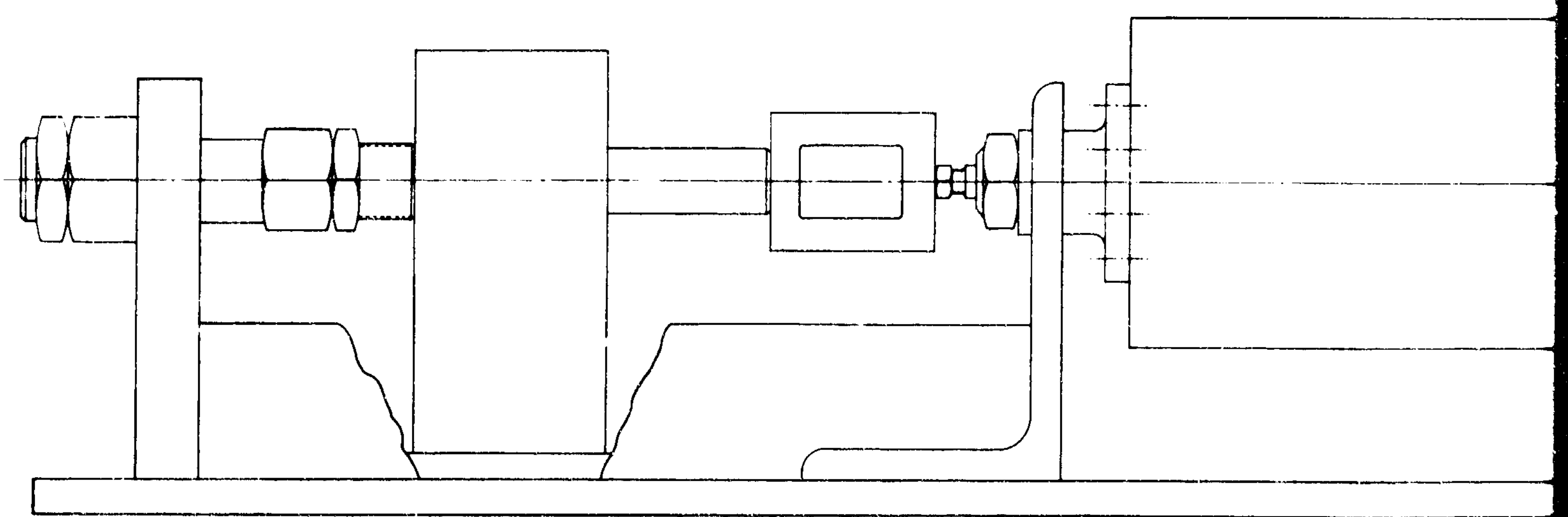
g = gravitational constant

$\dot{W}$ = mass flow

ρ = density of fluid

J = a conversion factor (Joules equivalent)


BELLOWS SEAL
FORMED 321 SS
SHAFT END FLANGE
UPSTREAM PRESSURE PORT
BODY SECTION



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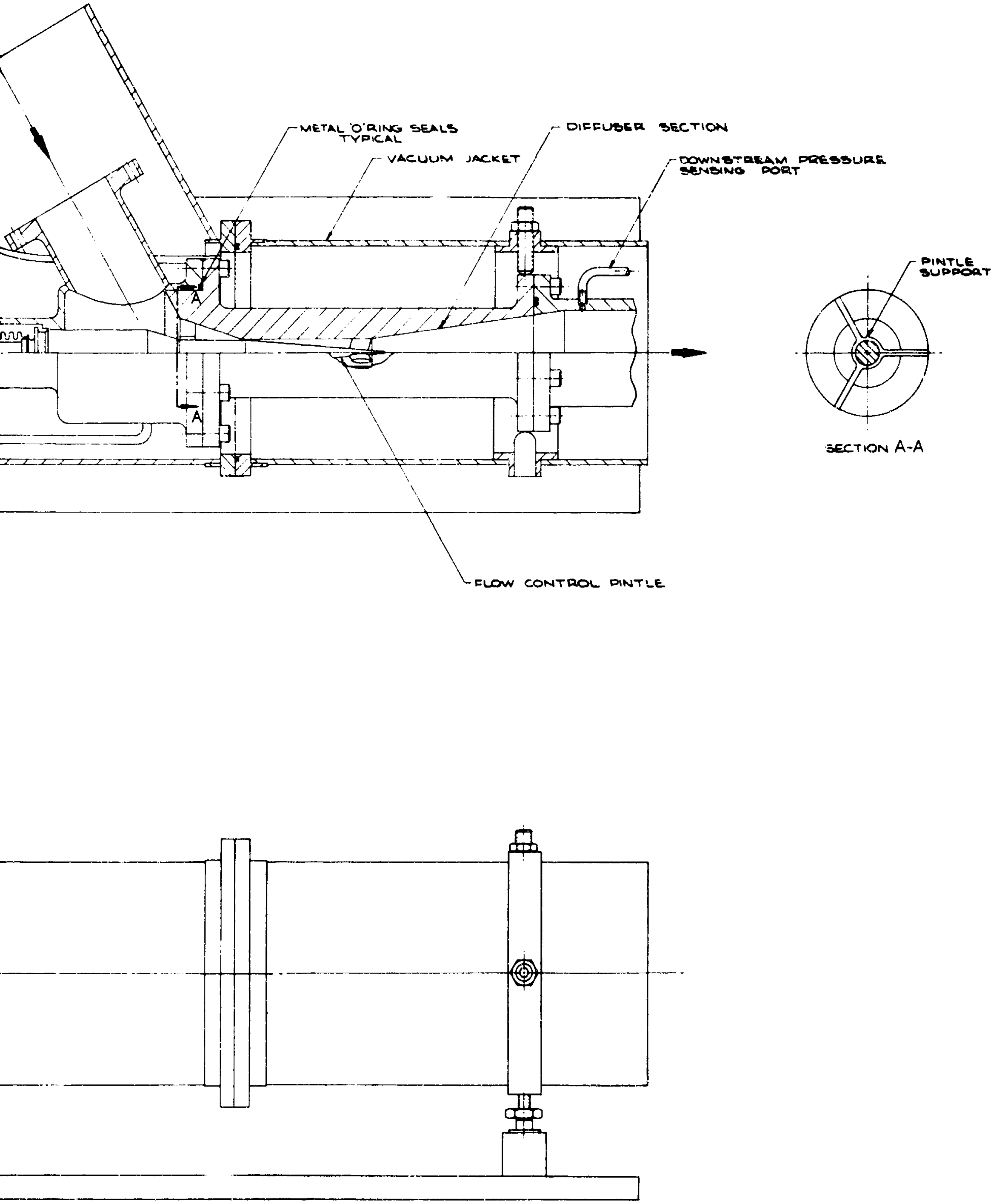


Figure 2. Liquid Hydrogen Valve Cross Section

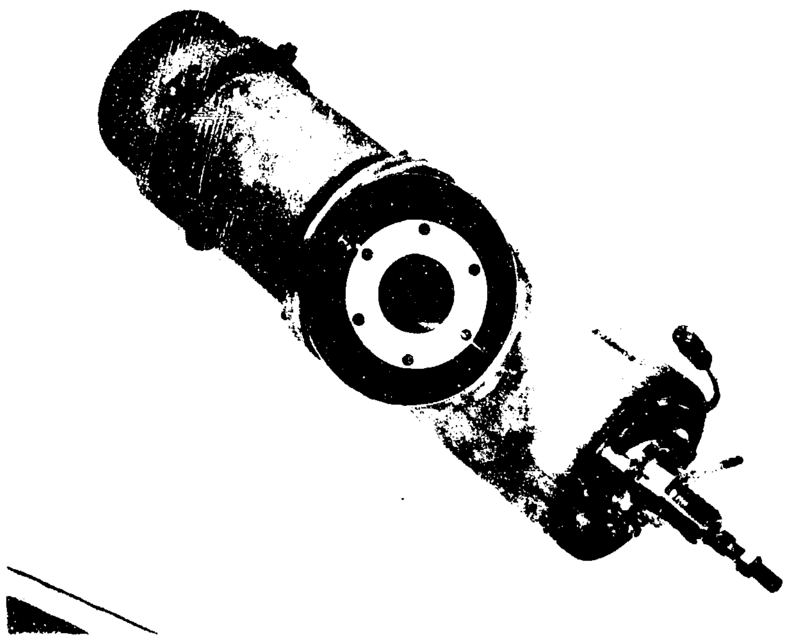


Figure 3. Liquid Hydrogen Valve Assembly

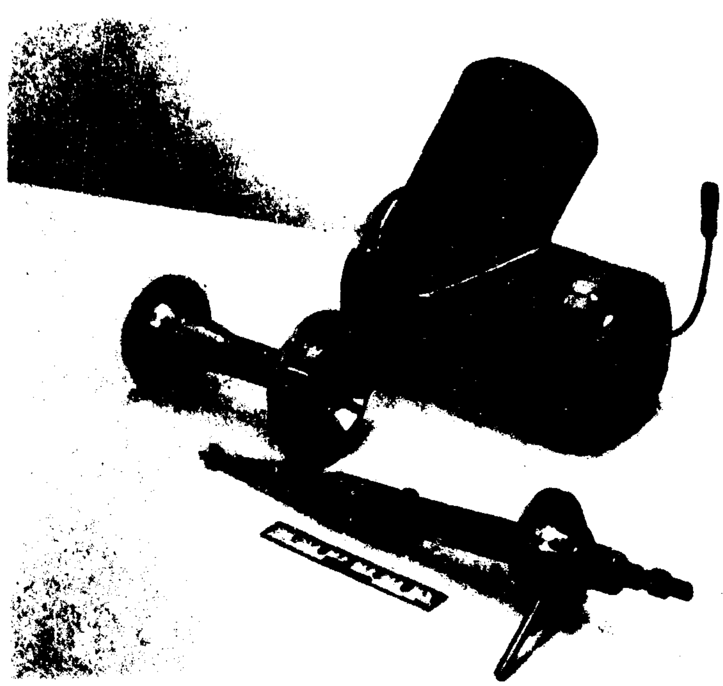


Figure 4. Liquid Hydrogen Valve Disassembled

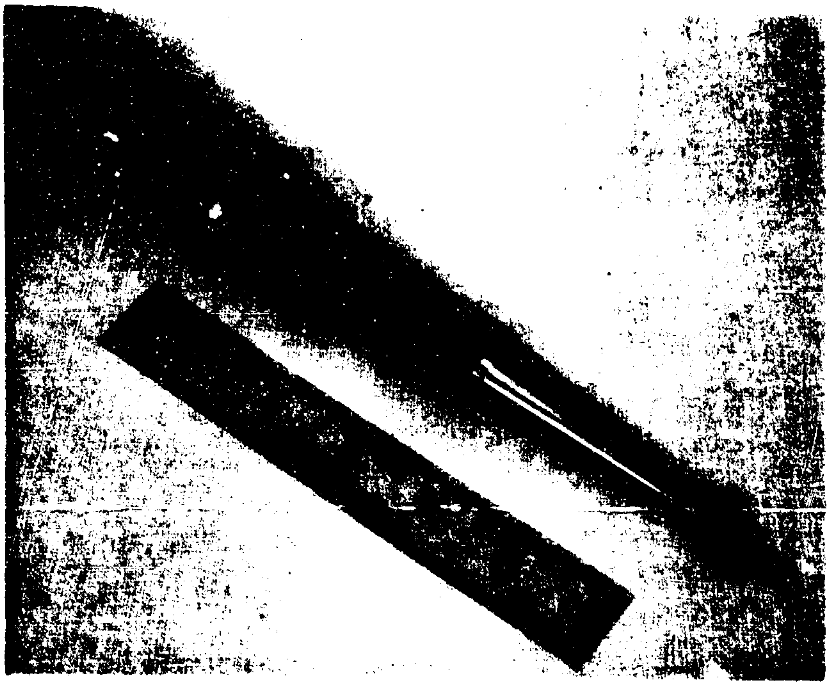


Figure 5. Liquid Hydrogen Valve Pintle

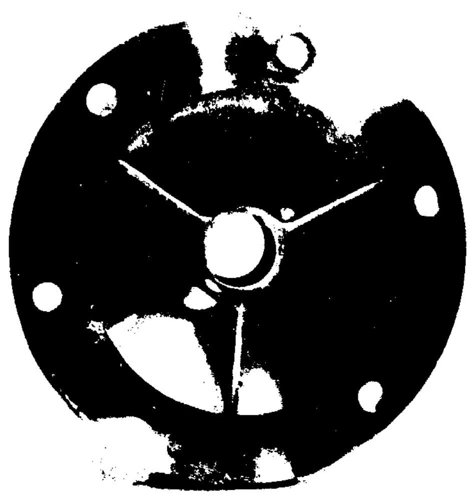


Figure 6. Liquid Hydrogen Valve Throat and Inlet Support

For the valve design the throat area at 100 percent flow was established and the areas for other flow rates determined proportionally on a linear basis. The predicted cavitation line location was estimated by establishing a curve on the basis of a noncavitating flow calculation and extrapolating to determine the intersection with the cavitating flow rate. This was tempered with the experience from previous flow data.

This approach was used to determine the predicted parameters shown on the flow charts (see Test Results, Figures 13 and 14). For the case of water flow, the relationship for noncompressible liquids was used where:

$$A = \frac{12 \dot{W}}{C_d \sqrt{2g \rho (P_1 - P_v)}}$$

and:

P_1 = valve inlet pressure

P_v = vapor pressure of fluid at inlet temperature.

The design flow conditions for the valve are:

Hydrogen mass flow at 100 percent throttle, $\dot{W}_F$, = 2.88 lb/sec

Inlet pressure, P_1, = 465 ±20 psia

Inlet temperature, T_1, = 37° to 60°R

Recovery to be as great as possible at the 100 percent flow setting on the cavitation line.

3.2 DESIGN DETAILS

As described in Reference 1, and shown in Figure 2, the valve is of all-metal stainless steel design incorporating a bellows shaft seal. Vacuum jacketing is provided for insulation. The valve body and duct joints are sealed with unvented, 321 stainless steel, teflon coated O rings. An internal stop is provided beyond the theoretical zero flow pintle position. By calibrating the valve from the stop position, the unit may be disassembled for cleaning without the necessity of flow test after reassembly. The inlet pressure tap is located in the inlet plenum and brought out through the vacuum jacket by a welded-in small-diameter tube.

The pintle drive support fixture previously used for the mixture ratio control was simplified for the monopropellant application. Jamb nuts are employed for the valve positioning. Accurate positioning is achieved with a dial indicator mounted on the fixture and driven from an arm attached to the valve shaft.

Modifications made to the valve during the water test sequence are covered under Test Results, Section V of this report. A vibration problem encountered earlier in the program ultimately required addition of a support at the throat inlet.

SECTION IV

TEST FACILITY

The system installed by Wyle Laboratories and used during the performance of the test program is shown schematically in Figure 7 and in photographs, Figures 7 through 11.

The liquid hydrogen supply vessel was a 250-gallon capacity stainless steel tank, fitted with an outer shell which was filled with liquid hydrogen. This outer jacket of liquid hydrogen served as the refrigerant for the liquid-hydrogen within the 250-gallon run tank. The entire assembly was insulated by spraying the outer surfaces with approximately one inch of polyurethane foam.

Ambient temperature hydrogen gas was used to maintain the run tank at the desired 465 ±10 psia. To obtain greater pressure stability, the 3500 psig hydrogen storage gas pressure was dropped to 1100 psig through a first-stage regulator, then subsequently reduced to the running pressure through a parallel pair of second-stage regulators. To minimize mixing of the warm pressurant gas and cold test fluid, a diffuser was installed in the top of the run tank. This diffuser assembly also served as a manifold for the four, 4.2-cubic-foot ullage bottles which served to dampen pressure transients during the test runs.

Flow measurements were made using two Foxboro turbine flowmeters. The low-rate meter was used when operating between 0.03 and 0.60 pound per second, and the high-rate meter when operating between 0.35 and 3.0 pound per second. Water calibrations were performed on both meters prior to performing the test program, and the meter coefficient value was increased by 0.60 percent to compensate for the thermal contraction and subsequent velocity increase within the meter housing when operating at the reduced temperature. During the program, several data points were run in the over-lapping range of the flowmeters, approximately 0.35 to 0.60 pound per second, and the measured flow rates compared.

To minimize temperature transients and heat leak into the system, all of the plumbing between the run tank and test specimen inlet was jacketed with liquid hydrogen. Plumbing downstream of the specimen was insulated with glass-matt or foam insulation. The test specimen itself was housed in a vacuum jacket, shown in Figure 10. This jacket was evacuated continuously throughout the program.

Flow control was achieved using two 1-inch valves in parallel; one was a long stroke throttling valve with a remote operator, and the other a manual gate valve. The manual valve was pre-set as required to provide increased capacity to the remotely operated throttling valve.

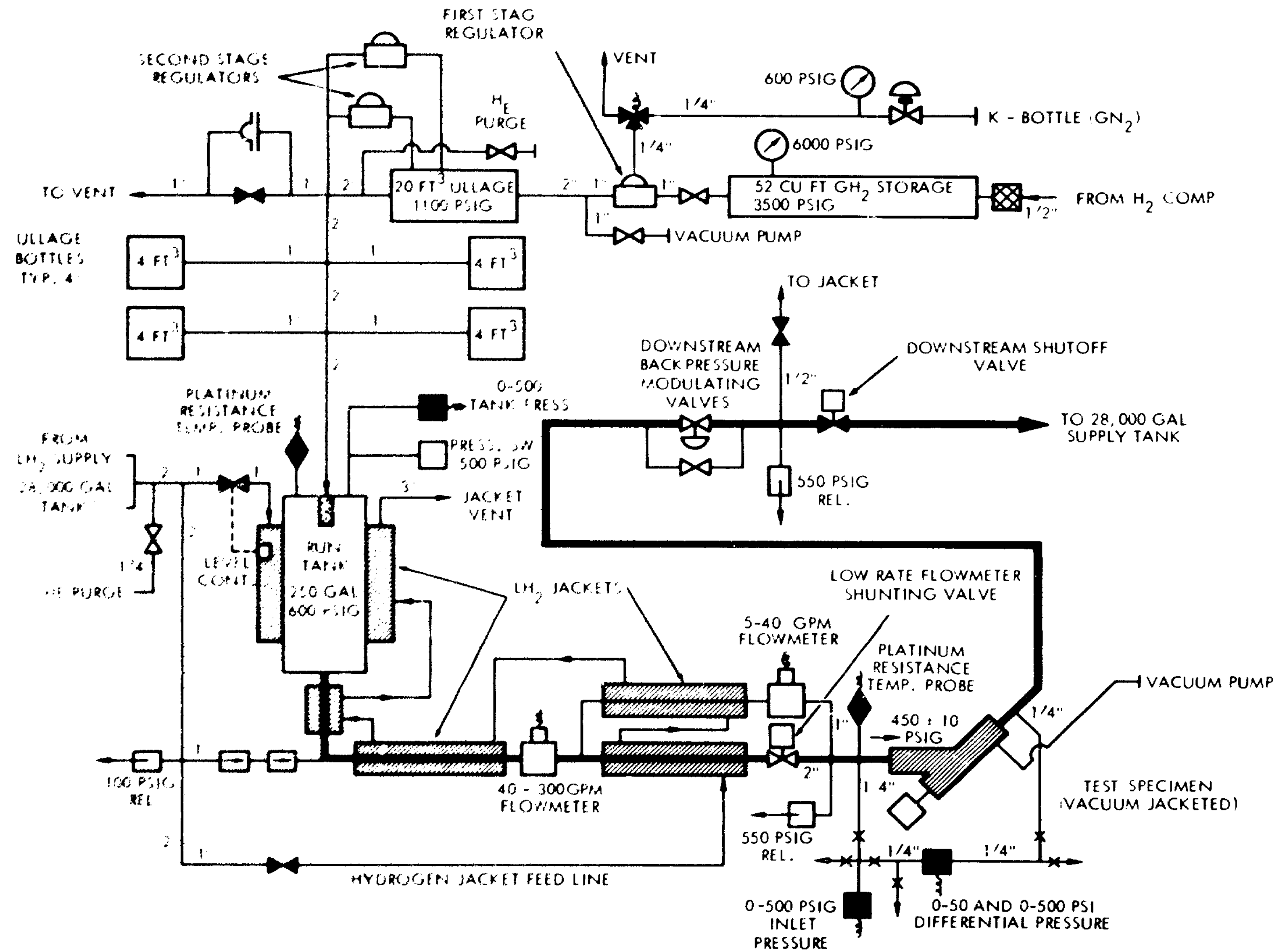


Figure 7. Liquid Hydrogen Flow Facility Schematic Diagram

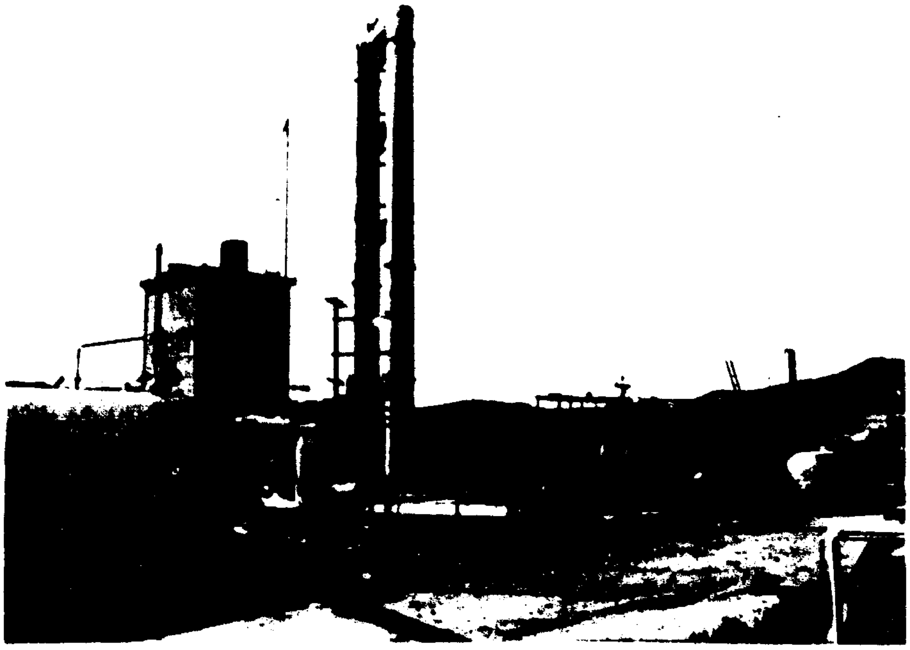


Figure 8. Overall View of Liquid Hydrogen Flow Facility

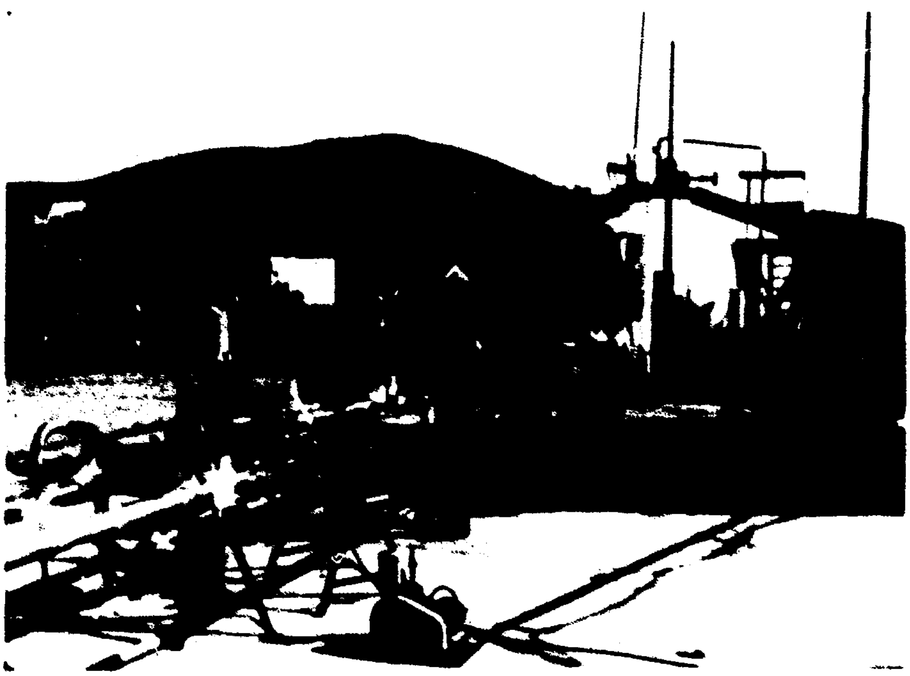


Figure 9. Liquid Hydrogen Facility Looking Downstream

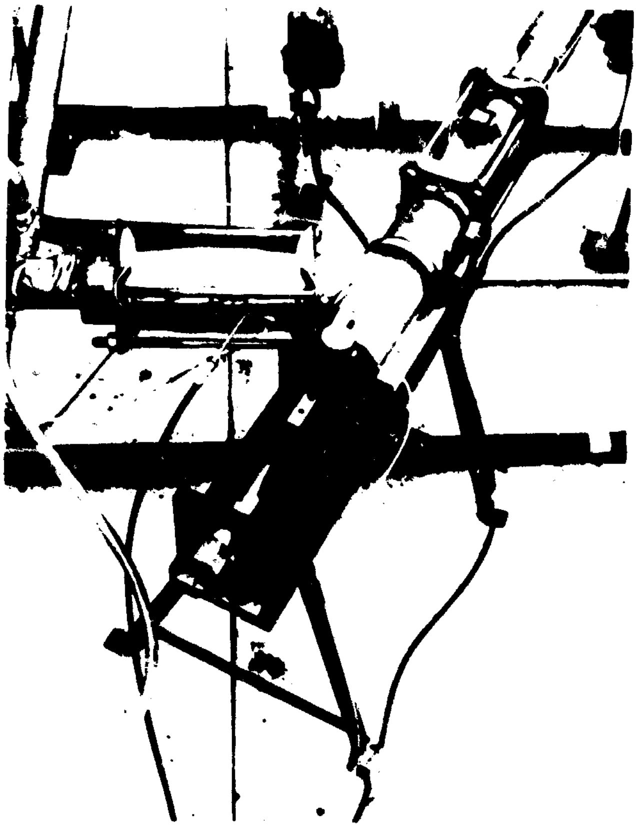
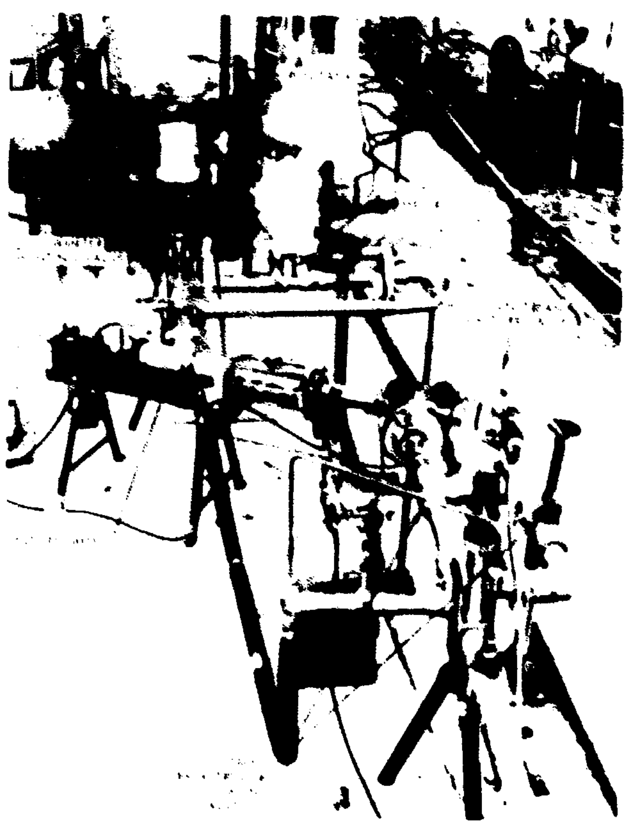


Figure 10

Test Valve Installed in
Flow System

Figure 11

Liquid Hydrogen Facility
Looking Upstream



Downstream of the flow control valves, a 2-inch fast-response operator valve was installed to start and stop the hydrogen flow. By presetting the flow control valves and controlling the flow duration with an independent valve of much higher response, it was possible to stabilize the flow rate quickly and hold the total run duration at each flow point to approximately ten seconds.

The hydrogen temperature was measured between the flowmeter manifold outlet and the test specimen inlet port, utilizing a Rosemount Engineering Company platinum resistance probe and matched resistance bridge.

SECTION V

TEST PROCEDURES

The following procedures were established for operation of the flow system. (Refer to schematic, Figure 7). Prior to test operations the system was stabilized at the liquid hydrogen temperature. All tanks, lines, and jackets were first vacuum purged with helium. The jacket system was then filled with LH_2 and chilled-down. Following this the run tank and jacketed lines were filled with liquid hydrogen. With the test valve set at the 100% flow position an initial flow was established through the system by pressurizing the run tank to a low pressure and throttling the downstream modulating valve.

With the system temperature conditioned for test, the test valve was set to the first throttling position to be flowed. With the downstream shutoff valve closed the run tank was pressurized to obtain the normal run inlet pressure of 465 psia. With the downstream back pressure modulating valve preset to obtain a pressure drop across the test valve in the desired range the flow was initiated by opening the downstream shutoff valve. For each flow point taken the shutoff valve was opened for 5 to 10 seconds to allow the flow to stabilize, then closed. Steady state data recorded for each run included flowrate, inlet pressure and temperature and valve differential pressure. Run tank pressure and temperature were monitored to observe system operation. The objective of the test effort was to obtain a minimum of 120 flow points over 12 different throttle flow settings and in pressure drop ranges making possible evaluation of the cavitation pressure line over the flow range.

Emptying of the run tank was easily determined when the temperature sensor in the run line indicated a rapid temperature increase. At this point the downstream shutoff valve was closed and the run tank vented and refilled from the storage tank. It was then repressurized. It was found once the system was well chilled-down, flow could be resumed within 10 minutes after refill.

SECTION VI

TEST RESULTS

With completion of the flow test program, the feasibility of applying a variable-area cavitating-venturi valve to throttle control of liquid hydrogen was established. The control performance was demonstrated with supercritical pressure conditions prevailing at the valve inlet. Although the liquid hydrogen flow results varied slightly from predicted values, the data obtained were for the most part consistent and repeatable. A pintle vibration problem observed earlier was essentially eliminated.

Table I provides a summary of liquid-nitrogen, water, and liquid-hydrogen tests completed. Plotted flow data for water and liquid hydrogen are given in Figures 13 and 14, respectively. The liquid-nitrogen test was run early in the program using the liquid-fluorine valve to observe the effect of bore clearance reductions with the pintle support fins in eliminating a vibrational problem observed in earlier tests in the later part of 1967. Inasmuch as the same vibrational problem had occurred with the hydrogen valve the plan was to implement the same solution if effective. The vibration was not eliminated, however, and it was obvious that other solutions would have to be applied to the liquid hydrogen valve.

5.1 WATER FLOW TESTS

In order to verify the previously observed hydrogen valve vibration a preliminary water flow test was run at the TRW Capistrano Test Site. Audible vibration was encountered at flow settings from 2 up to 35 percent. The greatest sensitivity was apparent at 10 percent and lower settings with the vibration continuing over a broad range of differential pressures. At 35 percent the vibration was only initiated near the cavitation line. No quantitative data were taken during this test.

At this point a vibration analysis was initiated to evaluate the modes of vibration and consider the effect of potential modifications (see Appendix I). Two easily implemented changes which could provide a solution were apparent. The mass of the pintle could be increased by filling the internal cavity with a high-density material or an added bearing support could be located near the mid-span point of the pintle. The first approach was taken. A port was drilled into the cavity and 158 grams of lead shot was introduced. The port was then closed with a threaded plug. Since the originally sealed cavity now had a potential leak path, additional vent holes were drilled. This was necessary to ensure hydrogen could not be trapped in the cavity with subsequent potentially dangerous pressure buildup upon warm-up.

A second water test was run with the weighted pintle. Some improvement was observed with the vibration occurring only below the 20 percent setting. A frequency measurement was made with an accelerometer located on the valve outer body near the downstream flange support. Frequencies

Table I. Liquid Hydrogen Test Summary

19 November 1968	Liquid-nitrogen tests of the fluorine valve were completed to determine if reducing pintle fin clearances eliminated pintle vibration. Vibration was still observed at lower throttle settings.
30 December 1968	A preliminary water-flow test of the hydrogen valve was run to verify the vibration previously observed in tests run in 1967. Vibration was observed from 2 percent up through settings as high as 35 percent.
7 January 1969	A water-flow test was run to observe the effect of adding mass to the pintle. Vibration was still experienced at settings of 20 percent and below.
17 January 1969	A water-flow test was run following addition of a pintle support immediately upstream of the throat. A transitory vibration was observed at settings below 7 percent flow.
23 January 1969	Water-flow tests were completed and calibration of the valve established. No vibration was experienced
11 March 1969	The valve was delivered to Wyle Laboratory for the hydrogen flow tests following a refurbishment and cleaning.
31 March 1969	Hydrogen-flow tests were started at Wyle Laboratories.
11 April 1969	Hydrogen-flow tests were successfully completed.

in the range of 900 to 1100 Hz were observed. The vibration condition was still considered unacceptable for initiation of the liquid hydrogen flow tests.

A spider support was designed for location upstream of the throat (Figures 2 and 6). Initially the valve was designed for such additional support and the pintle shape and entry portion of the throat section had been designed for easy installation of a bearing. The shot weighting was left in the pintle cavity. Water tests were repeated with the added support. An intermittent higher frequency vibration was observed at flow settings of 7 percent and below. A measurement indicated the vibration frequency had increased to a range of 1700 to 1900 Hz. The region of vibration observed is plotted in Figure 12. The apparent effect of the added support was to change the vibrational mode with an approximate 1 octave upward

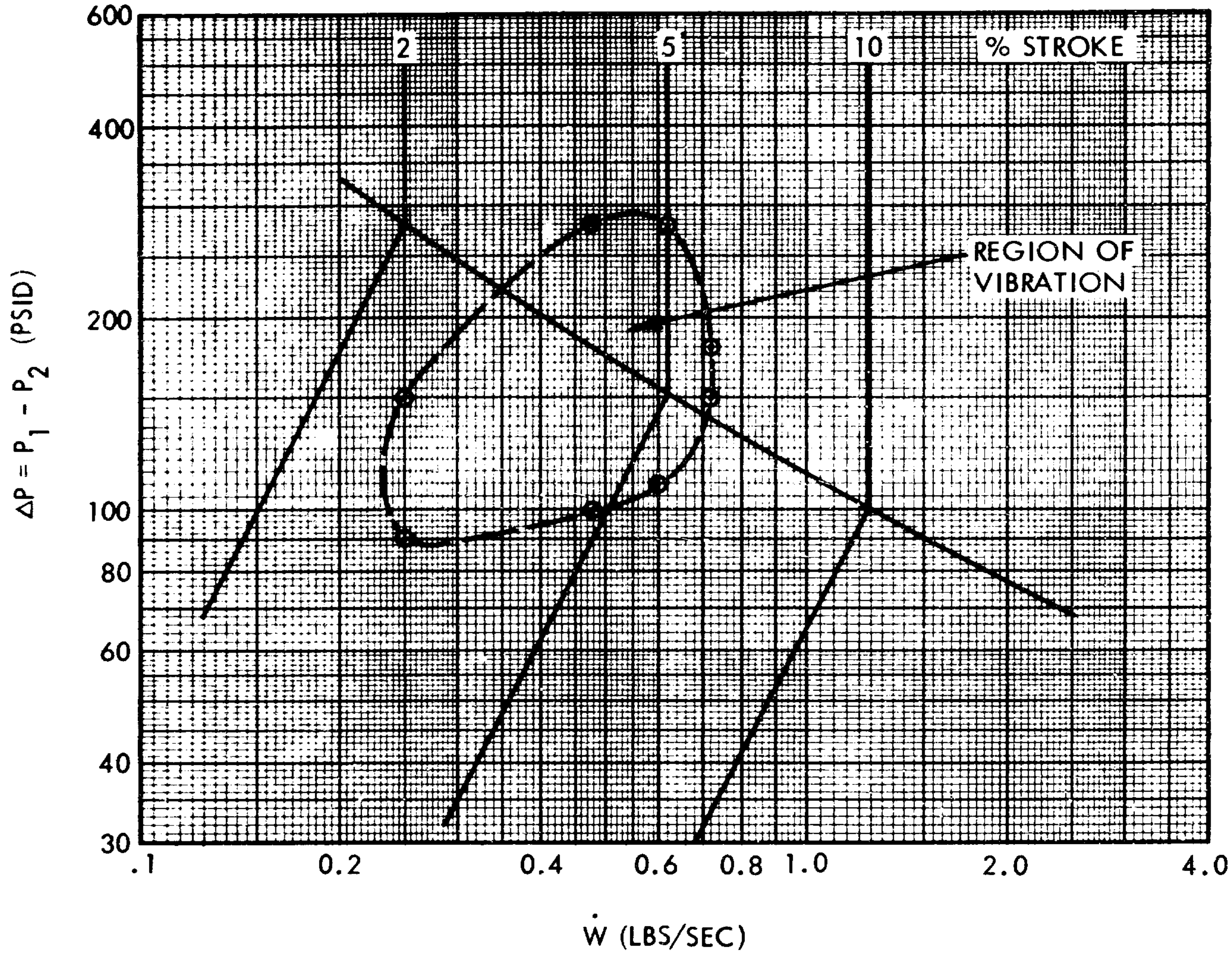


Figure 12. Liquid Hydrogen Valve Region of Vibration

shift. The vibration did not appear to change the flow control characteristic of the valve as shown by moving into and out of the vibrational region in the cavitating mode.

Upon review of the effects of the remaining vibration it was concluded the valve was sufficiently improved to continue with the water and liquid-hydrogen flow tests. The valve was then calibrated and runs made over the flow range shown in Figure 13. The flow rates were limited to 60 percent and below because of the pressure-flow capacity limit of the available water pump flow system. The calibration point was established by accurate measurement from the internal stop. The technique was to calibrate for the 2 percent flow position where the adjustment is most sensitive. To illustrate the sensitivity of the adjustment in the range of 2 percent flow, the effect on flow of a 0.002 shift in setting is indicated on the chart, Figure 13.

5.2 LIQUID HYDROGEN FLOW TESTS

Following completion of the water test and calibration, the valve was returned to TRW Space Park for preparation for the liquid hydrogen tests. The valve was disassembled and cleaned. A roughness had developed at the outer guide bearing of the valve at the shaft extension. This was reworked. All bearing contacting surfaces of the pintle were treated with a Microseal* coating to prevent any further galling between the stainless surfaces. The valve was carefully reassembled and calibrated based on the stop dimension determined from the water tests. The specimen was then shipped to Wyle-Norco for setup in the test system and testing. The test plan established with Wyle Laboratories appears in Appendix II.

The flow tests were accomplished starting 31 March through 11 April 1969. Two days were spent in flowing the system for familiarization and adjustments of instrumentation and facility controls. Aside from initial difficulty in obtaining consistent results with the high-range flowmeter, the system operated as planned. A backup flowmeter was substituted. Consistent results were then obtained as well as good agreement with the low-range meter. Discrepancies in the overlapping range did not exceed ±1 percent. Operation of the system proved to be simple and efficient. The initial cool-down required approximately one hour. Instrumentation calibration was typically completed during this same period. It was found that three to five data points could be obtained with a single filling at high flow rates and ten to fifteen at low flow rates.

The flow data obtained are shown in Figure 14. It is apparent flows at the 2, 5, and 10 percent settings agreed quite well with the predicted values. Over the range from 20 through 110 percent they are consistently below the predicted flows. Assuming the differences to be effectively accountable as a shift in discharge coefficient, the data were interpreted

*Microseal Corporation, Gardena, California

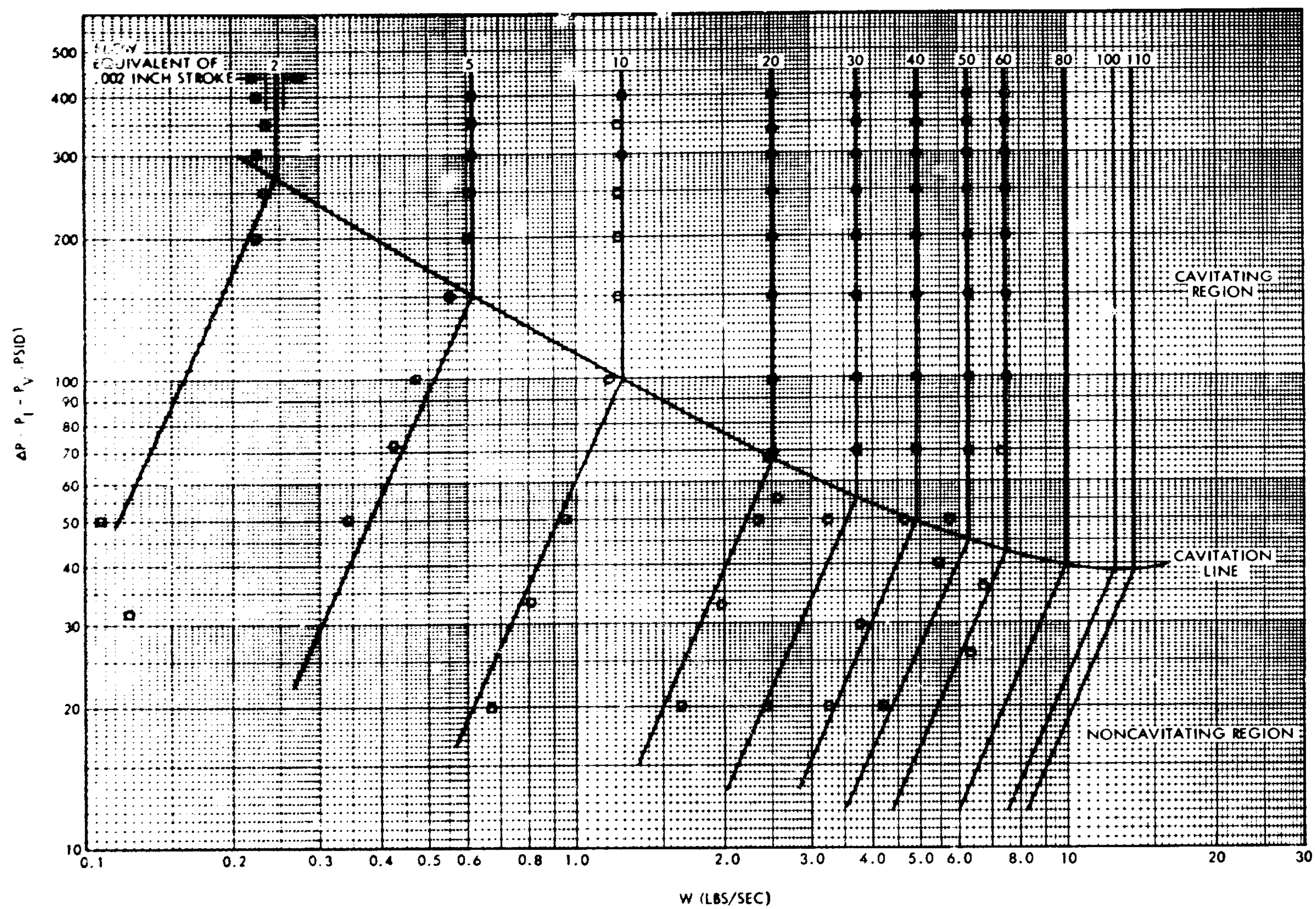


Figure 13. Water Flow Test Data

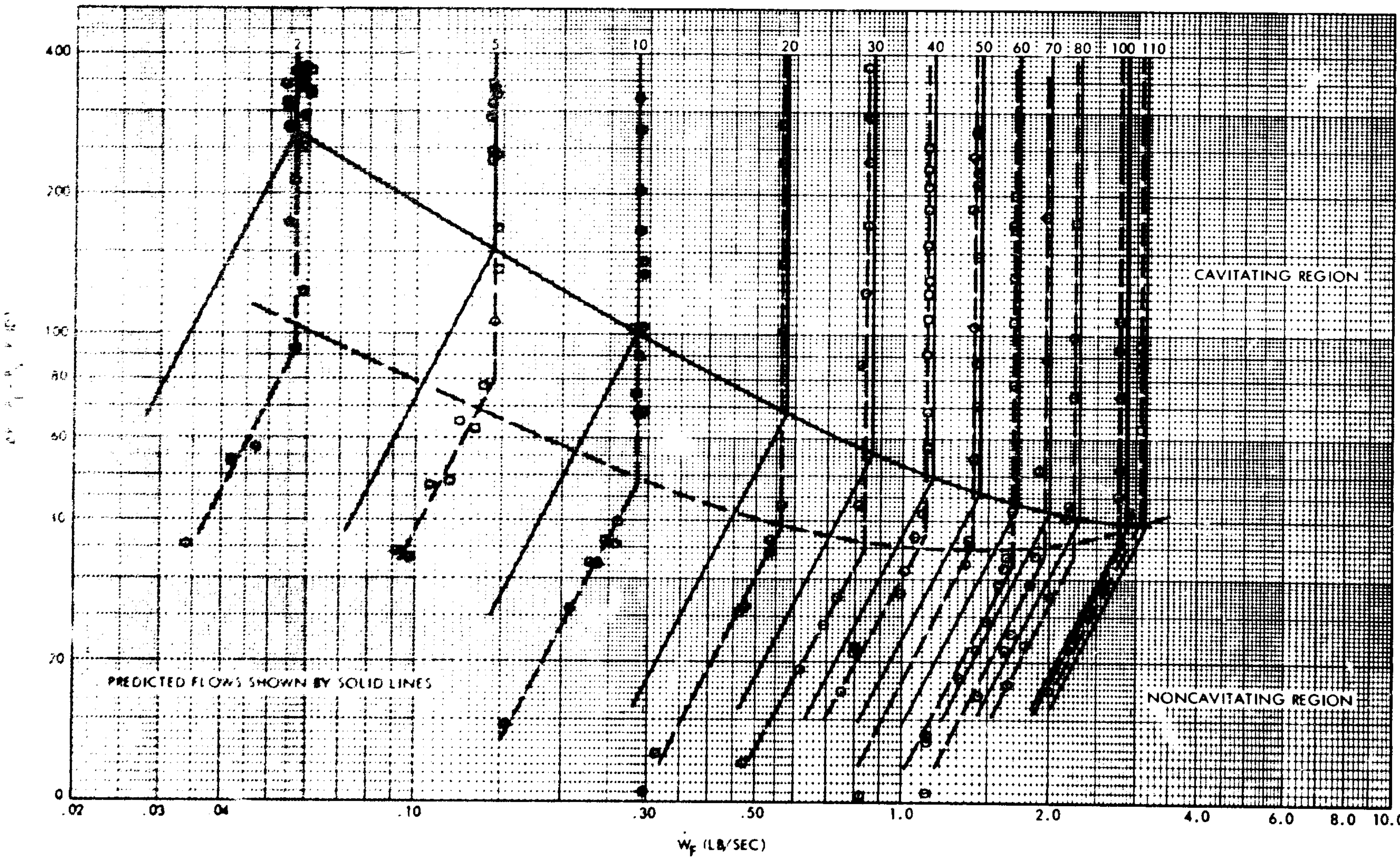


Figure 14. Liquid Hydrogen Flow Test Data

as can be seen in Figure 15. The discharge coefficient is plotted against the percentage flow settings. A constant coefficient of 0.875 is obtained from 20 to 110 percent. The flow points at 2, 5, and 10 percent show a coefficient of 0.9 as assumed in calculating the predicted flows.

All of the flow data were standardized from the observed conditions to the nominal design conditions assumed for the predicted curves (inlet pressure 465 psia and inlet temperature 51°R). Applying the principle given in Reference 2, Section 2, to correct the weight flow the equation:

$$\dot{w}^* = \dot{w}\sqrt{\frac{\rho^*}{\rho}\,\frac{P_1^* - P_v^*}{P_1 - P_v}}$$

is applied. For correction of the valve pressure drop the equation is:

$$\Delta P^* = \Delta P\left(\frac{P_1^* - P_v^*}{P_1 - P_v}\right)$$

where:

$\dot{w}^*$ Weight flow at nominal conditions

$\dot{w}$ Weight flow observed

ρ^* Density at nominal conditions of temperature and pressure

ρ Density for fluid at observed temperature and pressure

P_1^* Inlet pressure at nominal conditions

P_1 Inlet pressure at observed conditions

P_v^* Vapor pressure at nominal temperature

P_v Vapor pressure at observed temperature

ΔP Pressure difference from valve inlet (P_1) to valve outlet (P_2)

The corrections apply to both the cavitating and noncavitating flow regimes.

The original data sheets are given in Appendix III as part of the test report furnished by Wyle Laboratories. Because the test facility utilized a liquid hydrogen tank and lines, the runs were all made in the temperature range of 39 to 45°R. The jackets were operated at essentially atmospheric pressure with equilibrium temperatures close to 37°R. Referring to the temperature-entropy chart shown in Figure 1, the flow process was following a path near that shown by the ar v at the lower lefthand part of the chart.

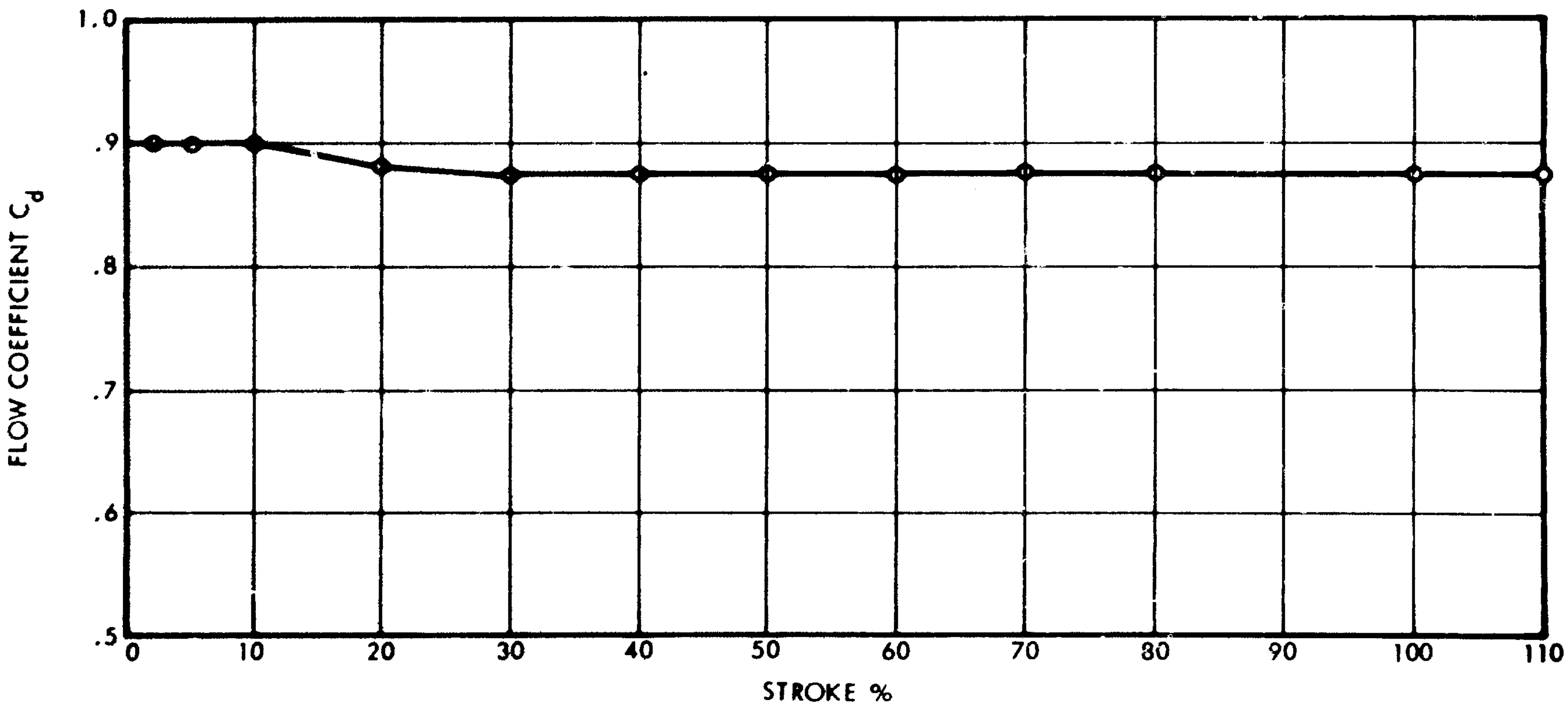


Figure 15. Flow Coefficient in Cavitating Region — Liquid Hydrogen Test

The location of the cavitation line was significantly changed as is apparent in Figure 14. The line is well below the predicted curve at all flow rates below 100 percent. This is reflected in pressure recovery of the valve on the cavitating line given by Figure 16. A recovery in the order of 92 percent is indicated over flow ranges from 20 to 100 percent.

In order to relate the results obtained by the flow test series to the effects of off-nominal tolerances within the valve itself, the pintle contour inspection data are plotted in Figure 17 in the form of off-nominal flow areas. As is apparent, the pintle was on the nominal dimensions up to the 17 percent flow point. Above 17 percent, above and below nominal pintle diameters were measured resulting in the opposite effect on flow area. It is interesting to note the maximum dimensional off-nominal flow area deviates by little more than 0. 1 percent. This accounts for a very small fraction of the total error potential in estimating the discharge coefficient as well as that contributed by flow, temperature, and pressure instrumentation required for flow testing.

Evidence of the audible vibration observed during water tests was experienced with liquid hydrogen. The vibration only occurred below 5 percent flow and was intermittent in character and could not be predictably initiated at any flow or differential pressure. No effect on flow rate in cavitation was observed when vibration was evident.

Following completion of the hydrogen flow tests the valve was disassembled and the parts inspected. No evidence of wear of damage was evident. The photographs, Figure 3 through 6, were taken at the time of inspection.

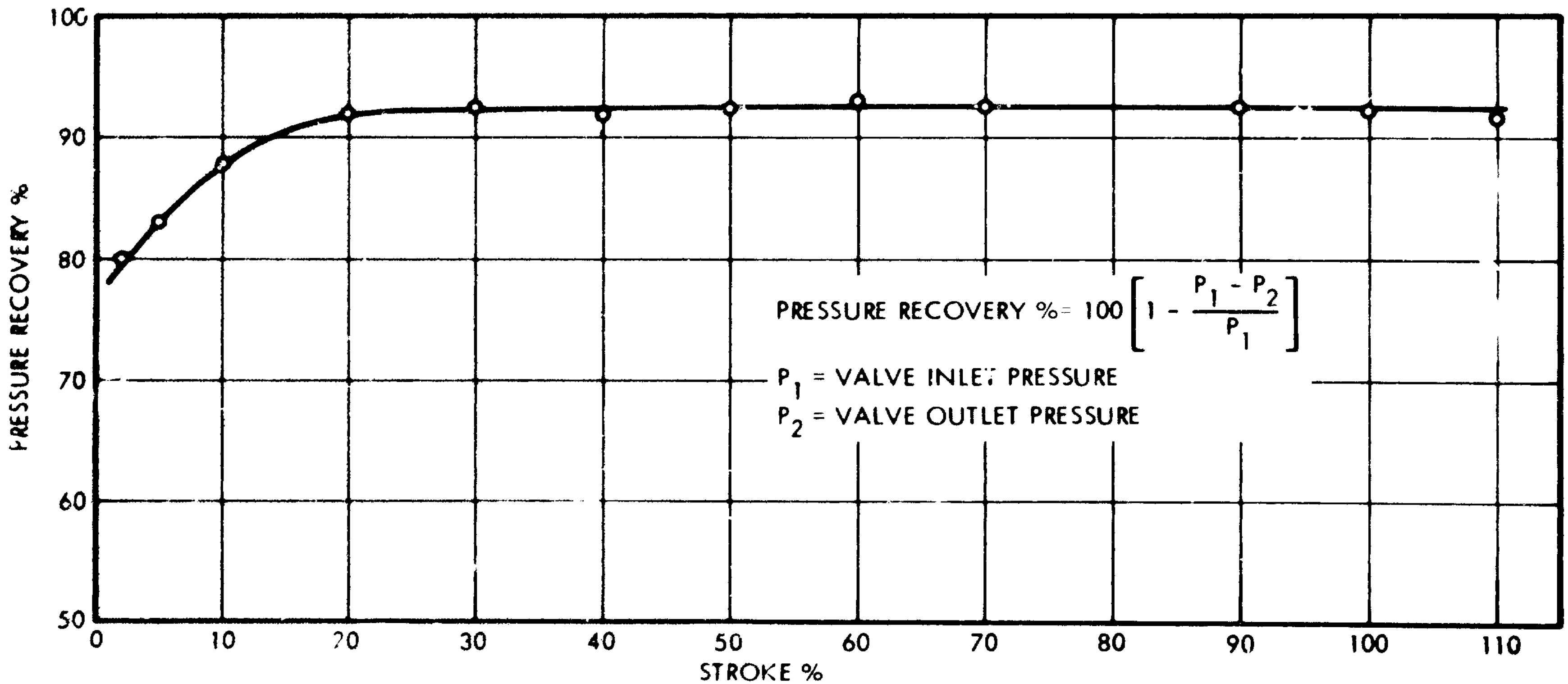


Figure 16. Pressure Recovery on Cavitation Line

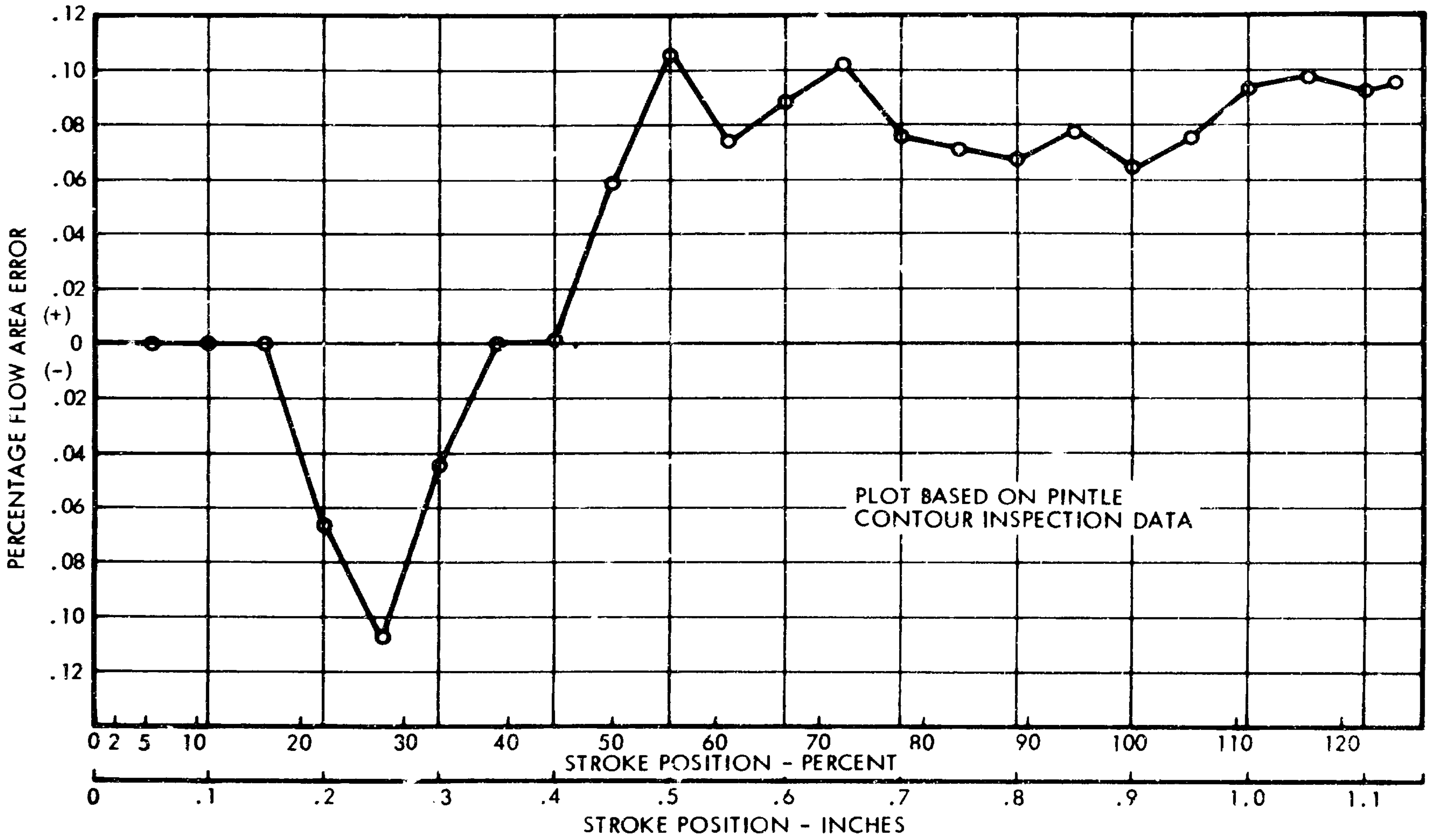


Figure 17. Pintle Contour Error for Liquid Hydrogen Valve

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

As a result of the flow test series it is apparent the cavitating venturi is a useful technique for accurate flow control of liquid hydrogen. Application of the data presented to refine the first-cut contours for a flight design component will be useful. It is also apparent the valve can easily be fabricated to attain geometric accuracies far exceeding those attainable from the combined test instrumentation required to evaluate flow performance. It was also demonstrated the valve can be designed to be disassembled after water calibration, cleaned or overhauled, and reassembled without effecting accuracy or making recalibration necessary.

Because of the limitations of the test system, temperatures little above the normal boiling temperature of hydrogen (37°R) could be attained. It is considered that changes in the flow control performance of the valve would be small up to the critical temperature (60°R), however. To completely explore the temperature range would require a conditioned flow system capable of steady-state operation. A larger test matrix would also be required to evaluate the range to 60°R and above.

It is recommended for future design that actual engine system conditions be established. From the present knowledge of the workhorse valve used in the program, a flight weight design can be established with a high degree of confidence. The valve can then be tested under actual expected conditions. Problems of vibration, control, and ultimate accuracy can be then resolved in a directly usable component.

SECTION VIII

APPENDICES

APPENDIX I

LIQUID HYDROGEN VALVE FREQUENCY ANALYSIS

T.A. ZEMO TRW SYSTEMS

Introduction

A study of the 15K LH_2 valve has been conducted to estimate the natural frequencies for various mass concentrations and support modes. The calculations are based upon idealizations, thus showing trends of frequency range rather than exact numbers. The objectives are (1) to determine whether the excitation source is a random noise signal or a fixed periodic signal, and (2) to make recommendations concerning a suitable correction for the existing vibration problem.

Discussion

Frequency calculations were made for the original LH_2 valve and for the same valve with 158 grams of lead added to the pintle cavity. In Table II, calculations based upon a cantilever beam idealization are compared to those for a double support, with variations for concentrated and distributed mass. These numbers are based upon Equation 1, using the respective values of the configuration coefficient, effective length and mass. The frequency is very sensitive to changes in the effective length and radial thickness (Equation 2) so that small refinements of these values in more recent calculations have affected the frequency estimations considerably.

Comparisons of the limited test data and analytical calculations relative to the LMDE system have shown that when excited by a stochastic (random noise) signal, each system component oscillates at its own natural frequency. The frequencies which had been indicated by an accelerometer mounted on the outside valve housing were in the 900 to 1100 Hz range. If the excitation was of a fixed periodic type, closed loop amplitude ratio (valve to excitation) considerations indicate that the most desirable correction would be by mass addition. This is shown in Figure 18. If enough of a high density material could be added to reduce the valve's natural frequency substantially below the excitation frequency, the oscillations would be attenuated. This would be achieved if the material could be distributed more uniformly through the pintle's interior. However, the major portion of the hydrogen pintle cavity is at the end nearest the bearing, so that the effective length is reduced (because of center of mass shift) as the mass is increased. The frequency is more sensitive to change in length than to change in mass (Equation 1) so that it rises (values 5, 6, 7, and 8 of Table I compared to values 1, 2, 3, and 4). The mass addition fix may be possible for the fluorine valve, with its geometry, but apparently not for the hydrogen valve. The water flow tests performed at the Capistrano facility showed that mass addition is not a sufficient correction for the LH_2 valve, as it still displayed the "screeching" and internal scoring at the throat.

Table II

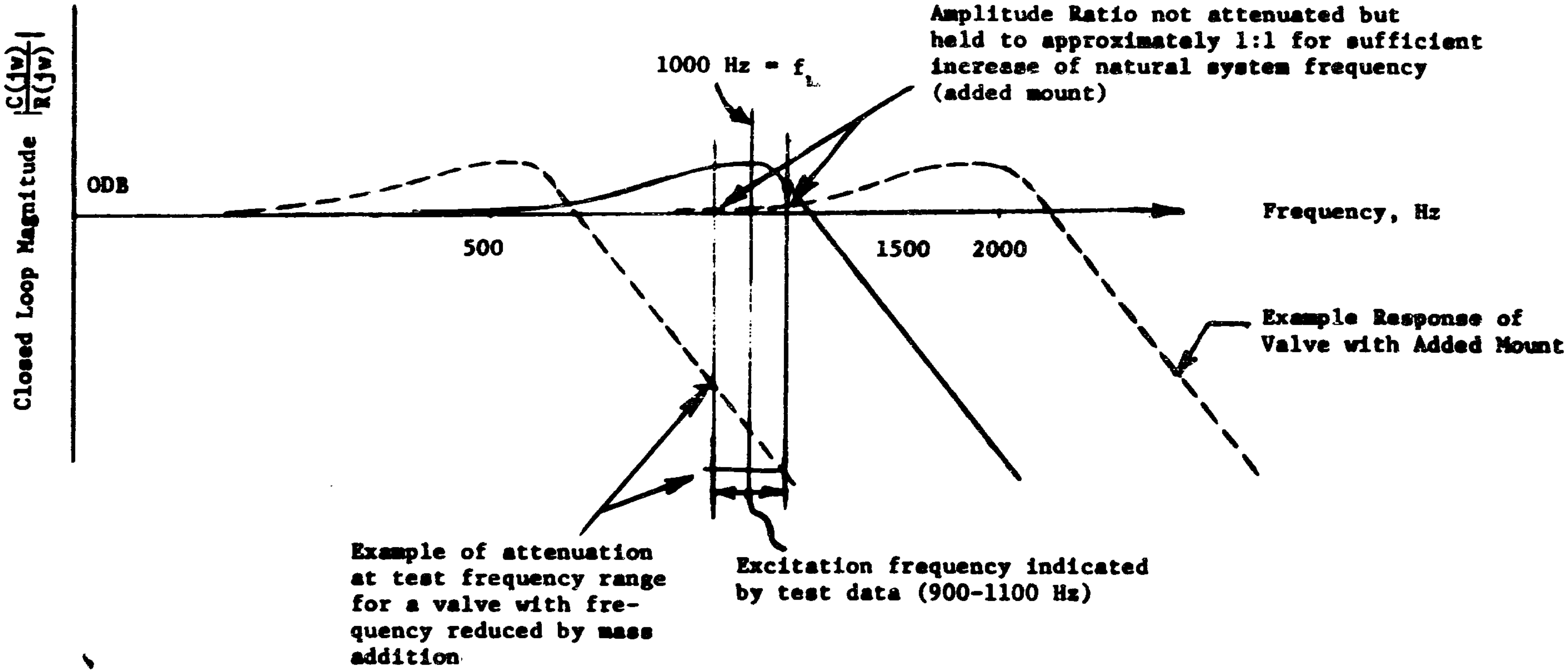
Comparative Calculated Vibration Characteristics

	Cantilever, Mass Concentrated At End	Cantilever, Mass Distributed	Double Support Mass Concentrated At Center	Double Support Mass Distributed
Original Valve	(1)	(2)	(3)	(4)
f(Hz)	1378	2839	3858	5511
A	0.275	0.566	1.1	1.571
ℓ(in)	5.273	5.273	6.69	6.69
M(#sec^2/in)	2.541×10^{-4}	2.541×10^{-4}	2.541×10^{-4}	2.541×10^{-4}
Valve with Lead Added	(5)	(6)	(7)	(80
f(Hz)	2098	4321	1929	2755
A	0.275	0.566	1.1	1.571
ℓ(in)	3.977	3.977	6.69	6.69
M(#sec^2/in)	10.168×10^{-4}	10.168×10^{-4}	10.168×10^{-4}	10.168×10^{-4}

Conclusions

It is recommended that the support be added as planned, approximately one inch upstream of the throat for the valve's zero thrust position. Calculations were made for the balance of bending moments and maximization of frequency characteristics resulting after the addition of the support at that point. These are based upon the relative thickness and diameter ratios of the two hollow segments. However, further reference to Figure 1 indicates that a tight clearance bearing fit is advisable for the mount. Although added instrumentation is not planned for upcoming tests, it is necessary for any further evaluation of the excitation characteristics. This would consist of strain gages mounted in positions suitable for determination of valve inlet and outlet pressure fluctuations, with accelerometers and pressure transducers in positions adjacent to the strain gages.

LMDE test data has shown that: (1) if several strain gages are placed at different locations and there is a correlation in frequency, amplitude and phase of the outputs, it can be assumed the outputs represent internal pressure fluctuations; and (2) a correlation with pressure transducer and accelerometer readings is advisable for conclusive evaluation regarding the causes. An objective of this instrumentation would be the construction of power spectral density plots. In addition to frequency trends with system changes, conclusions may be made about the amplitudes recorded. Although a component tends to ring at its own (constant) frequency when excited by a random signal, its amplitude varies randomly, in a pattern dependent upon the excitation frequency spectrum and the component's damping ratio.



*Assumes that valve is being excited by a 900-1100 Hz driving frequency; if the source is random (white noise) then the valve will oscillate at its resonant frequency.

Figure 18. Closed Loop Amplitude Ratio (Valve to Excitation) Frequency Response*

Nomenclature

Parameter	Symbol	Value
Young's modulus of elasticity	E	30×10^6 psi
Cross-section (bending) moment of inertia	I	312×10^{-4} in^4
Structural configuration coefficient	A	
Effective length for vibration in each configuration	ℓ	See Table II
Effective mass for each configuration	M	
Frequency for each configuration	f	

Equation (1) $f = \frac{A}{\ell 1.5} \quad \frac{EI}{M}$

(2) $I = \frac{\pi}{4}\left(R_o^4 - R_i^4\right)$

APPENDIX II

TEST PLAN
LIQUID HYDROGEN CAVITATING VALVE FLOW TESTS

Test Objectives

The required tests are part of the Wide Range Flow Control Program for LF_2-LH_2 under Contract AF04(611)-10819 sponsored by the Rocket Propulsion Laboratory at Edwards AFB. The general objectives of the program are to establish propellant flow control valve technology for the noted cryogenic propellants. The liquid hydrogen test called for in this plan is the last phase of the effort.

The specific objective of the LH_2 flow tests is to substantiate the flow control predicted for the cavitating venturi test valve. The operating characteristic and flow control accuracy will be evaluated over the design flow range of the component and under the flow conditions indicated below.

Program Requirements

The test component will be delivered to the Wyle Norco Test Site by TRW per a mutually agreed schedule. The requirements for installation will be established a reasonable time in advance of the first test date to allow for system buildup and instrumentation. The test section will be as noted in Figure 19. The instrumentation requirements are as noted in Table III.

Table III. Instrument Requirements

Parameter	Range	Units	Required Accuracy
Mass flow $\dot{w}$	0.055 to 3.0	lbs/sec	±1.0%
Inlet pressure P_1	465 ±10	psia	±0.5%
Outlet pressure P_2	10 to 400	psig	±1.0%
Differential pressure ΔP	10 to 400	psi	±1.0%
Inlet temp T_1	40 to 80	^oR	±1 ^oR
Valve position X	o to 0.900	inch	±0.001 inch

The vendor is requested to furnish a schematic of the flow facility giving pertinent details such as line sizes, tank sizes, heat exchanger characteristics, and instrumentation. A component list is requested.

Suitable photographs of the facility and detail views of the test setup at the time of test are also requested.

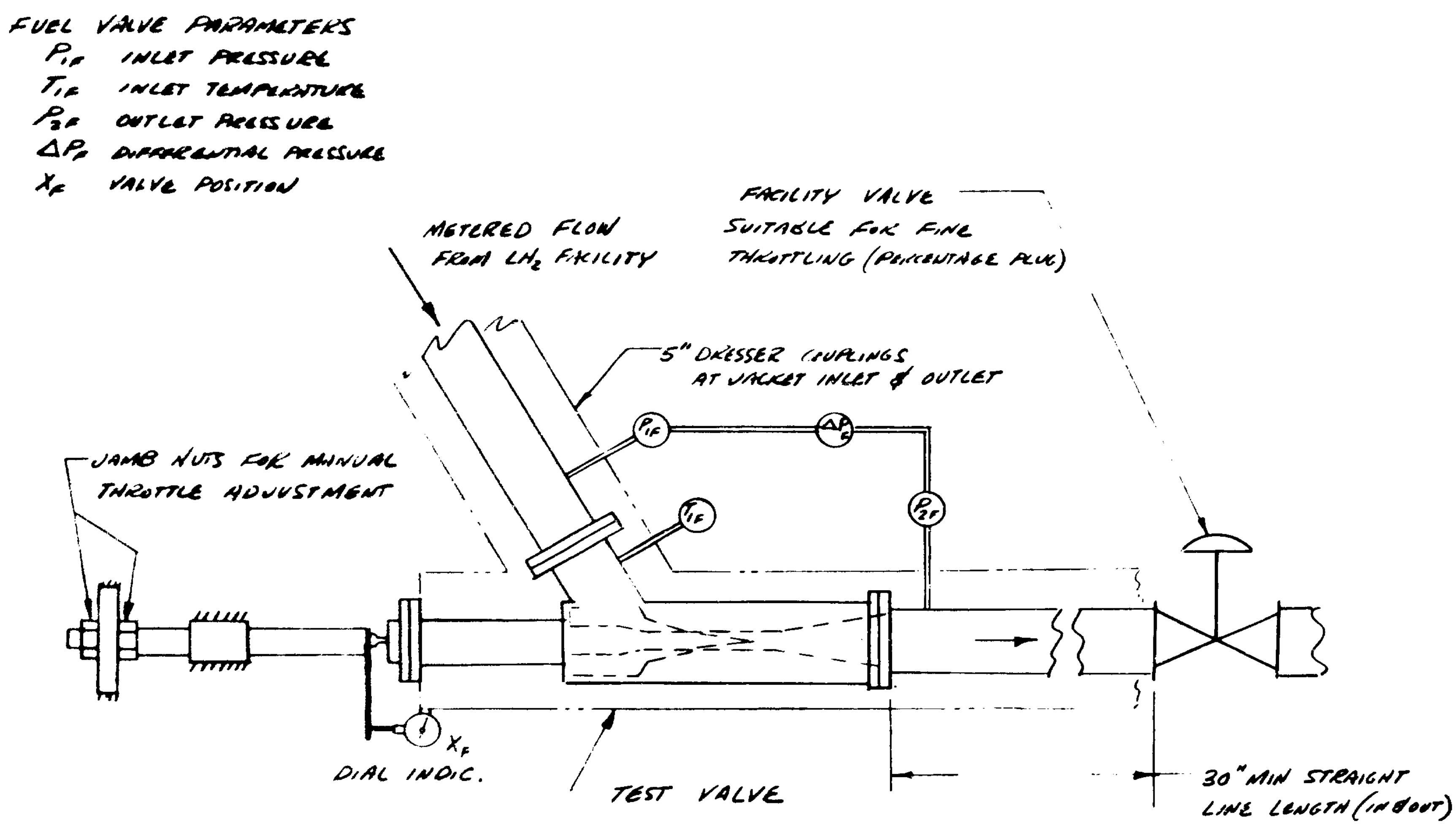


Figure 19. LH_2 Cavitating Valve Test Section Schematic

Original data or facsimile are to be supplied. The vendor is requested to reduce data as required to provide time based traces with directly readable scales ir the final units of measure. Traces should be time scaled alike for direc overlay comparison.

Propellants in the following quantity are provided for (GFP) under the contract.

Liquid Hydrogen FSN 9135-611-1347	20,000 lb
Gaseous Helium FSN 6830-660-0026	60,000 SCF

Test Requirements

The test component will be installed in the flow facility per the test section schematic, Figure 19. The flow test objective will be to obtain a series of 120 flow-points over the range of throttle and pressure drop settings given in the predicted flow map.* A series of 10 flow points will be obtained over a range of pressure drop settings at each of the following percentage throttle valve settings: 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 100, 110.

The inlet pressure throughout the series will be held to 465 ±10 psia.

The inlet temperature will be held in the range of 40 to 65 °R throughout all the runs.

The theoretical flow rate for the valve at the 100 percent setting and at an inlet pressure of 465 psia and an inlet temperature of -409 °F (51 °R) is 2.88 lb/sec. The other flow settings are linearly proportional to the valve position.

From previous experience the recommended testing technique is to first set the test valve at the specified throttle position. With the downstream facility valve closed, or nearly closed, the inlet pressure is increased to the required level. A low differential pressure exists across the test valve under those conditions. The facility valve is then incrementally opened to pick up each of the desired differential pressure points. The points when reduced to the established standard conditions may be expected to fall on the curve for the particular throttle position set as shown on the flow map.

*See Figure 14 of this report.

APPENDIX III

WYLE LABORATORIES TEST REPORT

DATA SHEET REPORT

WYLE LABORATORIES

28 APRIL 1969

TRW
1 SPACE PARK
REDONDO BEACH, CALIFORNIA 90278

ATTENTION:		MR. MIKE CONSOLI
TEST TITLE:		FLOW TEST
REFERENCES:	Your Purchase Order No.	BK 266
	Wyle Laboratories Job No.	NL 51393
	Government Contract No.	N/A
	Wyle Laboratories Report No.	51393

Gentlemen:

This is to certify that the enclosed Test Data Sheets contain true and correct data obtained in the performance of the test program as set forth in your purchase order.

Where applicable, instrumentation used in obtaining this data has been calibrated using standards which are traceable to the National Bureau of Standards.

Test Results:

LIQUID HYDROGEN FLOW TESTING OF ONE CAVITATING VENTURI VALVE P/N SK 4715-68-147, IN ACCORDANCE WITH TEST PLAN 4715.1.68-43 AND THE ABOVE PURCHASE ORDER. TEST RESULTS ARE INCLUDED ON THE FOLLOWING PAGES.

28 PAGE TEST REPORT

STATE OF CALIFORNIA } ss.
COUNTY OF RIVERSIDE }

ROY C. SADLIER, being duly sworn, deposes and says: That the information contained in this report is the result of complete and carefully conducted tests and is to the best of his knowledge true and correct in all respects.

Roy C. Sadlier

SUBSCRIBED and sworn to before me this 28TH day of APRIL, 19 69

Catherine J. Kelly
Notary Public in and for the County of Riverside, State of California

My Commission expires 14 JULY, 19 71

DEPARTMENT LIQUID PROPELLANTS TEST

DEPT MGR R. C. Myrick
R. C. MYRICK

TEST ENGINEER H. R. Wheelock
H. R. WHEELOCK

TEST WITNESS

DCAS QAR VERIFICATION

QUALITY CONTROL A. Heeseman
A. HEESEMAN

W-731

TEST SYSTEM DESCRIPTION

THE SYSTEM USED DURING THE PERFORMANCE OF THE TEST PROGRAM IS SHOWN IN FIGURE 7* AND PHOTOGRAPHS 1 THROUGH 4.*

THE LIQUID HYDROGEN SUPPLY VESSEL WAS A 250 GALLON CAPACITY STAINLESS STEEL TANK, FITTED WITH AN OUTER SHELL WHICH WAS FILLED WITH LIQUID HYDROGEN. THIS OUTER JACKET OF LIQUID HYDROGEN SERVED AS THE REFRIGERANT FOR THE LIQUID HYDROGEN WITHIN THE 250 GALLON RUN TANK. THE ENTIRE ASSEMBLY WAS INSULATED BY SPRAYING THE OUTER SURFACES WITH APPROXIMATELY ONE INCH OF POLYURETHANE FOAM.

AMBIENT TEMPERATURE HYDROGEN GAS WAS USED TO MAINTAIN THE RUN TANK AT THE DESIRED 465 ±10 PSIA. TO OBTAIN GREATER PRESSURE STABILITY, THE 3500 PSIG HYDRO STORAGE GAS PRESSURE WAS DROPPED TO 1100 PSIG THROUGH A FIRST AGE REGULATOR, WHEN SUBSEQUENTLY REDUCED TO THE RUNNING PRESSURE THROUGH A PARALLEL PAIR OF SECOND STAGE REGULATORS. TO MINIMIZE MIXING OF THE WARM PRESSURANT GAS AND COLD TEST FLUID, A DIFFUSER, SHOWN IN PHOTOGRAPH 1, WAS INSTALLED IN THE TOP OF THE RUN TANK. THIS DIFFUSER ASSEMBLY ALSO SERVED AS A MANIFOLD FOR THE FOUR, 4.2 CUBIC FOOT ULLAGE BOTTLES WHICH SERVED TO DAMPEN PRESSURE TRANSIENTS DURING THE TEST RUNS.

FLOW MEASUREMENTS WERE MADE USING TWO FOXBORO TURBINE FLOWMETERS. THE LOW RATE METER WAS USED WHEN OPERATING BETWEEN 0.03 AND 0.60 POUNDS PER SECOND, AND THE HIGH RATE METER WHEN OPERATING BETWEEN 0.35 AND 3.0 POUNDS PER SECOND. WATER CALIBRATIONS WERE PERFORMED ON BOTH METERS PERFORMING THE TEST PROGRAM, AND THE VALUE OF THE METER COEFFICIENT INCREASED BY 0.60% TO COMPENSATE FOR THE THERMAL CONTRACTION AND SUBSEQUENT VELOCITY INCREASE WITHIN THE METER HOUSING WHEN OPERATING AT THE REDUCED TEMPERATURE. DURING THE PROGRAM, SEVERAL DATA POINTS WERE RUN IN THE OVERLAPPING RANGE OF THE FLOWMETERS, APPROXIMATELY 0.35 TO 0.60 POUNDS PER SECOND, AND THE MEASURED FLOW RATES COMPARED. THIS DATA IS PRESENTED IN FIGURE 5 AND SHOWS A DISCREPANCY OF +1.0% TO -1.0% OCCURRING IN THE LIMITED RANGE WHERE BOTH METERS COULD BE OPERATED SIMULTANEOUSLY.

TO MINIMIZE TEMPERATURE TRANSIENTS AND HEAT LEAK INTO THE SYSTEM, ALL OF THE PLUMBING BETWEEN THE RUN TANK AND TEST SPECIMEN INLET WAS JACKETED WITH LIQUID HYDROGEN. PLUMBING DOWNSTREAM OF THE SPECIMEN WAS INSULATED WITH GLASS-MATT OR FOAM INSULATIONS. THE TEST SPECIMEN ITSELF WAS HOUSED IN A VACUUM JACKET, SHOWN IN PHOTOGRAPH 2*, AND THIS JACKET WAS PUMPED CONTINUOUSLY THROUGHOUT THE PROGRAM.

*For photographs 2 and 3 see Figures 10 and 11 page 15. For Figure 7 see Figure 7 Page 13.

TEST SYSTEM DESCRIPTION (CONTINUED)

FLOW CONTROL WAS ACHIEVED USING TWO ONE-INCH VALVES IN PARALLEL, ONE A LONG STROKE THROTTLING VALVE WITH A REMOTE OPERATOR, THE OTHER A MANUAL GATE VALVE. THE MANUAL VALVE WAS PRE-SET AS REQUIRED TO PROVIDE INCREASED CAPACITY TO THE REMOTELY OPERATED THROTTLING VALVE.

DOWNSTREAM OF THE FLOW CONTROL VALVES, A TWO-INCH FAST RESPONSE OPERATOR VALVE WAS INSTALLED TO START AND STOP THE HYDROGEN FLOW. BY PRE-SETTING THE FLOW CONTROL VALVES AND CONTROLLING THE FLOW DURATION WITH AN INDEPENDENT VALVE OF MUCH HIGHER RESPONSE, IT WAS POSSIBLE TO STABILIZE THE FLOW RATE VERY QUICKLY AND HOLD THE TOTAL RUN DURATION AT EACH FLOW POINT TO APPROXIMATELY TEN SECONDS. THE HYDROGEN TEMPERATURE WAS MEASURED BETWEEN THE FLOWMETER MANIFOLD OUTLET AND THE TEST SPECIMEN INLET PORT, UTILIZING A ROSEMOUNT ENGINEERING COMPANY PLATINUM RESISTANCE PROBE AND MATCHED RESISTANCE BRIDGE. UNDER THE TEST CONDITIONS, THE ERROR ASSOCIATED WITH THE TEMPERATURE MEASUREMENT IS LESS THAN $\pm 0.5^{\circ}$ R.

DATA REDUCTION

THE RECORDED TEMPERATURE PROBE RESISTANCE DATA WAS CONVERTED TO TEMPERATURE VALUES USING THE CURVE SHOWN IN FIGURE 1. THE SPECIFIC VOLUME OF THE HYDROGEN WAS TAKEN AT THE TEST TEMPERATURE AND PRESSURE FROM THE FAMILY OF CURVES SHOWN IN FIGURE 2.*

THE HYDROGEN FLOW RATE WAS CALCULATED FROM THE FOLLOWING EQUATION, USING THE APPROPRIATE METER CONSTANT:

$$\dot{W} = \frac{C\ F}{1000\ V}$$

$\dot{W}$ HYDROGEN FLOW RATE, LB/SEC

F METER FREQUENCY, HZ

V SPECIFIC VOLUME AT TEST CONDITIONS, FT^3/LB

C METER CONSTANT:

LOW RATE METER	0.2522
HIGH RATE METER	0.5290

FINAL DATA ADJUSTMENTS WERE MADE USING FIGURES 3* AND 4, TO CORRECT THE TEST DATA TO THE DESIGN INLET CONDITIONS OF 51° R AND 465 PSIA.

REPORT NO. 51393

WYLE LABORATORIES

PAGE NO. 5

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer TRW

Part No. NA

S/N NA

Spec. 4715.1.68-43

Para. N.A.

Job No. 51393

Date Test Started 4-3-69

Date Test Completed 4-7-69

Amb. Temp. NA

Photo YES

Test Med. HYDROGEN

Specimen Temp. AS NOTED

Specimen FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT^3/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}^*$ LB/SEC	ΔP^* PSID
1	2%	460	170	49.6	54.0	--	0.2410	0.056	0.055	167.1
2	2%	460	218	49.4	54.0	--	0.2405	0.057	0.056	213.4
3	2%	460	247	48.9	53.0	--	0.2391	0.056	0.054	239.3
4	2%	460	285	49.1	53.0	--	0.2399	0.056	0.055	277.3
5	2%	460	317	49.1	53.0	--	0.2399	0.056	0.055	308.4
6	2%	460	328	48.7	53.0	--	0.2388	0.056	0.054	316.9
7	2%	460	355	48.7	53.0	--	0.2388	0.056	0.054	342.9
8	2%	460	272	48.5	56.0	--	0.2384	0.059	0.057	261.9
9	2%	460	151	48.2	57.0	--	0.2374	0.061	0.059	144.5
10	2%	460	158	48.3	58.0	--	0.2375	0.062	0.060	151.4
11	2%	460	55	49.4	41.0	--	0.2405	0.043	0.042	53.9
12	2%	460	95	49.4	55.0	--	0.2405	0.058	0.057	93.0
13	2%	460	310	48.1	57.0	--	0.2372	0.061	0.059	296.4
14	2%	460	361	48.2	56.0	--	0.2374	0.060	0.058	345.5
15	2%	459	155	48.3	58.0	--	0.2377	0.062	0.060	148.8
16	2%	459	128	48.5	58.0	--	0.2386	0.061	0.059	123.5
17	2%	459	60	48.3	46.0	--	0.2377	0.049	0.047	57.6
18	2%	459	37	48.7	33.0	--	0.2390	0.035	0.034	35.8

Tested By R. LEMUS

Specimen Meets Spec. Requirements Yes ☐ No ☐

Witness ____ Date: ____

Sheet No. ____ of ____

Approved [signature] Date: 4/28/69

W 614 · Q. C. Form Approval [signature]

REPORT NO. 51393

WYLE LABORATORIES

PAGE NO. 6

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Job No. 51393

Date Test Started: 4-3-69

Date Test Completed: 4-11-69

Part No. NA

S/N NA

Amb. Temp. NA

Spec. 4715.1.68-43

Photo: Yes

Para. N.A.

Test Med. HYDROGEN

Specimen Temp. As Noted

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}$* LB/SEC	ΔP* PSID
1	5%	467	275.0	42.8	143	--	0.2255	0.160	0.143	239.3
2	5%	466	289.0	41.2	144	--	0.2230	0.163	0.144	248.5
3	5%	466	340.0	41.1	143	--	0.2230	0.162	0.143	292.1
4	5%	466	367.0	40.7	144	--	0.2220	0.164	0.144	313.8
5	5%	465	384.0	40.7	145	--	0.2220	0.165	0.145	328.7
6	5%	465	283.0	40.5	146	--	0.2215	0.166	0.146	242.2
7	5%	465	386.0	41.1	145	--	0.2230	0.164	0.145	332.0
8	5%	465	398.0	41.6	144	--	0.2235	0.162	0.144	344.3
1	5%	462	187.0	45.2	145	--	0.2307	0.159	0.147	169.8
2	5%	462	154.0	45.0	144	--	0.2302	0.158	0.146	139.5
3	5%	462	118.0	44.6	142	--	0.2293	0.156	0.143	106.4
4	5%	462	86.0	44.9	137	--	0.2300	0.150	0.138	77.8
5	5%	462	70.0	44.6	131	--	0.2293	0.144	0.132	63.1
6	5%	462	54.0	44.6	116	--	0.2293	0.128	0.118	48.7
7	5%	462	37.0	44.5	96	--	0.2292	0.106	0.097	33.2

Tested By: R. Lemus

Specimen Meets Spec. Requirements Yes ☐ No ☐

Witness: Date:

Sheet No. of

Q.C. Form Approval

Approved: Date: 4/28/69

W 614 A

REPORT NO. 51393

WYLE LABORATORIES

PAGE NO. 7

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-3-69

Date Test Completed: 4-7-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT^3/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}$* LB/SEC	ΔP* PSID
1	10%	463	120	40.5	280	--	0.2215	0.319	0.281	103.2
2	10%	465	195	40.3	287	--	0.2213	0.327	0.287	166.5
3	10%	464	239	40.1	287	--	0.2210	0.328	0.289	204.3
4	10%	464	307	40.3	288	--	0.2213	0.328	0.289	262.8
5	10%	464	322	40.0	289	--	0.2206	0.330	0.290	275.0
6	10%	464	376	40.9	288	--	0.2222	0.327	0.289	323.4
7	10%	464	169	40.1	292	--	0.2210	0.333	0.292	144.5
8	10%	464	42	40.1	258	--	0.2210	0.294	0.258	35.9
9	10%	464	80	40.1	293	--	0.2210	0.334	0.293	68.4
1	10%	456	16.0	44.8	151	--	0.2292	0.166	0.154	14.6
2	10%	455	29.0	43.7	205	--	0.2278	0.227	0.208	26.3
3	10%	455	36.1	43.4	224	--	0.2273	0.248	0.227	32.6
4	10%	454	77.5	43.1	286	--	0.2268	0.318	0.291	69.8
5	10%	454	40.0	43.3	242	--	0.2270	0.269	0.246	36.1
6	10%	454	151.0	43.0	287	--	0.2269	0.319	0.291	135.8
7	10%	454	83.0	42.9	287	--	0.2268	0.321	0.292	74.5
8	10%	454	114.0	42.9	287	--	0.2268	0.319	0.291	102.4
9	10%	453	43.5	43.3	257	--	0.2270	0.285	0.260	39.4
10	10%	453	57.0	43.3	284	--	0.2270	0.316	0.289	51.6
11	10%	453	100.0	43.4	288	--	0.2274	0.319	0.292	90.5
12	10%	453	35.5	44.5	231	--	0.2292	0.254	0.235	32.6

Tested By: R. LEMUS

Specimen Meets Spec. Requirements Yes ☐ No ☐

Witness ______ Date ______

Sheet No ______ of ______

W 614 A Q. C. Form Approval [illegible]

Approved [illegible] Date 4/21/69

REPORT NO. 51393

PAGE NO. 8

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-1-69

Date Test Completed: 4-3-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT^3/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}^*$ LB/SEC	ΔP^* PSID
1	20%	459	30.0	40.2	460	--	0.2215	0.524	0.464	26.0
2	20%	468	10.0	41.8	--	118	0.2235	0.279	0.247	8.6
3	20%	468	12.5	40.4	--	140	0.2215	0.334	0.293	10.6
4	20%	467	31.0	40.0	--	227	0.2205	0.544	0.476	26.3
5	20%	467	166.0	39.8	--	270	0.2205	0.647	0.565	140.3
6	20%	466	277.0	39.8	--	269	0.2205	0.645	0.564	234.3
7	20%	468	333.0	40.0	--	268	0.2205	0.643	0.562	281.7
8	20%	468	51.5	40.0	--	267	0.2205	0.641	0.560	43.6
9	20%	467	121.0	40.2	--	269	0.2210	0.644	0.564	102.7
1	20%	464	9.0	44.6	--	112	0.2291	0.259	0.238	8.1
2	20%	464	10.0	44.2	--	119	0.2284	0.276	0.252	8.9
3	20%	464	14.5	43.6	--	150	0.2272	0.349	0.310	12.8
4	20%	462	26.5	43.1	--	209	0.2265	0.488	0.433	23.4
5	20%	462	41.0	43.1	--	257	0.2265	0.600	0.532	36.2
6	20%	461	29.0	43.4	--	221	0.2270	0.515	0.466	25.8
7	20%	460	38.5	43.7	--	252	0.2275	0.586	0.535	34.4

Tested By: R. LEMUS

Specimen Meets Spec. Requirements: Yes ☐ No ☐

Witness: Date:

Sheet No. of

Q. C. Form Approval [signature]

W 614 A

Approved: [signature] Date: 7/28/69

REPORT NO. 51393

PAGE NO. 9

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-1-69

Date Test Completed: 4-4-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT^3/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}$* LB/SEC	ΔP* PSID
1	30%	464	50.0	42.2	--	387	0.2245	0.912	0.814	43.5
2	30%	464	50.0	41.8	--	388	0.2238	0.917	0.816	43.4
3	30%	463	133.0	41.5	--	396	0.2233	0.938	0.835	115.6
4	30%	463	132.0	41.5	--	396	0.2233	0.938	0.815	114.7
5	30%	463	144.0	41.3	--	397	0.2230	0.942	0.836	124.7
6	30%	463	100.0	41.8	--	397	0.2238	0.938	0.816	87.0
7	30%	463	199.0	42.0	--	399	0.2242	0.942	0.841	173.3
8	30%	464	269.0	42.5	--	400	0.2253	0.939	0.842	235.4
9	30%	467	336.0	42.8	--	402	0.2258	0.942	0.844	293.3
10	30%	464	32.0	41.3	--	350	0.2230	0.831	0.736	27.7
11	30%	467	28.0	41.2	--	328	0.2227	0.779	0.688	24.0
12	30%	467	22.5	41.7	--	293	0.2236	0.693	0.615	19.4
13	30%	467	14.0	41.7	--	224	0.2236	0.530	0.470	12.0

Specimen Meets Spec. Requirements Yes ☐ No ☐

Tested By: R. LEMUS

Witness: ______ Date: ______

Sheet No. ______ of ______

Approved: [signature] Date: 4/28/69

W 614 A Q.C. Form Approval [signature]

REPORT NO. 51393

PAGE NO. 10

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-1-69

Date Test Completed: 4-4-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

• TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE W LB/SEC	W* LB/SEC	ΔP* PSID
1	40%	463	262	41.4	--	528	0.2232	1.252	1.109	227.2
2	40%	462	296	40.5	--	532	0.2218	1.269	1.121	255.2
3	40%	462	243	40.4	--	532	0.2216	1.270	1.120	209.2
4	40%	462	219	40.3	--	532	0.2213	1.272	1.121	188.3
5	40%	461	142	40.3	--	532	0.2212	1.272	1.123	122.3
6	40%	460	183	40.2	--	532	0.2212	1.272	1.124	157.9
7	40%	460	106	40.4	--	532	0.2215	1.271	1.124	91.7
8	40%	460	126	40.5	--	532	0.2218	1.269	1.123	109.1
9	40%	460	54	41.2	--	531	0.2227	1.261	1.122	47.0
1	40%	470	29.0	43.1	--	427	0.2262	0.999	0.894	25.1
2	40%	469	32.5	42.6	--	456	0.2253	1.071	0.956	28.1
3	40%	469	36.5	42.3	--	480	0.2246	1.130	1.006	31.5
4	40%	468	43.0	42.4	--	505	0.2249	1.188	1.060	37.2
5	40%	467	48.5	42.1	--	520	0.2243	1.226	1.091	42.0
6	40%	468	80.0	42.3	--	530	0.2246	1.248	1.112	69.2
7	40%	467	66.5	42.6	--	531	0.2254	1.246	1.115	57.9
8	40%	467	148.0	44.2	--	531	0.2284	1.230	1.119	131.0

Specimen Meets Spec. Requirements Yes ☐ No ☐

Tested By: R. LEMUS

Witness: ______ Date: ______

Sheet No: ______ of ______

Approved: [illegible] Date: 4/28/69

Q. C. Form Approval [illegible]

W 414 A

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-2-69

Date Test Completed: 4-4-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOT[illegible]

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE W LB/SEC	W* LB/SEC	ΔP PSID
1	50%	464	6.1	41.8	--	262	0.2238	0.619	0.552	5.3
2	50%	464	12.0	41.2	--	387	0.2227	0.921	0.817	1[illegible].3
3	50%	462	22.1	40.7	--	533	0.2218	1.271	1.125	19.1
4	50%	462	31.0	40.8	--	617	0.2222	1.469	1.302	26.9
5	50%	464	42.0	41.4	--	653	0.2232	1.548	1.373	36.3
6	50%	461	81.0	42.2	--	668	0.2247	1.572	1.410	71.1
7	50%	469	123.0	41.5	--	663	0.2235	1.569	1.387	105.3
1	50%	460	218	40.9	--	662	0.2223	1.575	1.399	189.7
2	50%	460	282	40.6	--	662	0.2218	1.579	1.399	244.5
3	50%	460	315	40.5	--	663	0.2217	1.582	1.400	272.5
4	50%	459	320	40.4	--	664	0.2216	1.585	1.404	277.4
5	50%	459	171	40.4	--	665	0.2216	1.588	1.407	14[illegible].3
6	50%	459	258	40.6	--	668	0.2220	1.592	1.414	224.2
7	50%	459	242	41.3	--	667	0.2232	1.581	1.412	211.5
8	50%	459	100	41.1	--	664	0.2227	1.577	1.407	87.3
9	50%	458	42	40.5	--	646	0.2218	1.541	1.368	36.5
10	50%	458	58	40.5	--	660	0.2218	1.574	1.398	50.5

Tested By: R. LEMUS

Witness: ______ Date: ______

Specimen Meets Spec. Requirements: Yes ☐ No ☐

Sheet No ______ of ______

Approved: [illegible] Date: [illegible]/69

W 614 A Q. C. Form Approval [illegible]

REPORT NO. 51393

PART NO. 12

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-2-69

Date Test Completed: 4-2-69

Amb. Temp.: NA

Photo: YES

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE Ẇ LB/SEC	Ẇ* LB/SEC	ΔP* PSID
1	60%	468	10.8	41.7	--	434	0.2235	1.027	0.907	9.3
2	60%	466	21.5	41.1	--	626	0.2225	1.488	1.314	18.4
3	60%	465	24.7	40.4	--	672	0.2215	1.605	1.411	21.1
4	60%	465	28.7	40.4	--	713	0.2215	1.703	1.497	24.6
5	60%	466	34.3	40.9	--	749	0.2220	1.785	1.573	29.4
6	60%	465	48.2	42.3	--	781	0.2250	1.836	1.641	41.9
7	60%	469	>200	41.4	--	800	0.2230	1.898	1.666	171.0
8	60%	468	>200	40.9	--	798	0.2220	1.902	1.674	170.6
9	60%	473	16.5	41.0	--	538	0.2220	1.282	1.122	13.9
10	30%	472	16.1	41.0	--	536	0.2220	1.277	1.119	13.6
11	60%	467	37.0	41.2	--	766	0.2230	1.817	1.606	31.8
12	60%	469	39.0	42.2	--	77[illegible]	0.2245	1.824	1.622	33.6
1	60%	463	28.3	41.12	--	711	0.2229	1.688	1.496	24.5
2	60%	463	123.0	41.50	--	799	0.2234	1.892	1.682	107.3
3	60%	462	153.5	41.78	--	800	0.2238	1.891	1.689	133.9
4	60%	462	89.0	42.87	--	800	0.2259	1.873	1.689	78.6

Tested By: R LEMUS

Specimen Meets Spec. Requirements Yes ☐ No ☐

Witness ________ Date ________

Sheet No ________ of ________

Q. C. Form Approval [illegible]

Approved [signature] Date [illegible]

REPORT NO. 51393

PAGE NO 13

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer TRW

Job No. 51393

Date Test Started 4-2-69

Part No. NA

Date Test Completed 4-2-69

S/N NA

Amb. Temp. NA

Spec. 4716.1.68-43

Photo yes

Para. N.A.

Test Med. HYDROGEN

Specimen Temp. As NOTED

Specimen FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE Ẇ LB/SEC	W* LB/SEC	ΔP* PSID
1	70%	462	12.0	42.2	--	522	0.2245	1.230	1.103	10.5
2	70%	460	19.5	41.9	--	677	0.2240	1.599	1.433	17.1
3	70%	465	24.8	41.2	--	775	0.2230	1.838	1.627	21.4
4	70%	462	26.5	41.2	--	797	0.2230	1.891	1.679	23.0
5	70%	462	33.6	41.2	--	867	0.2230	2.057	1.827	29.2
6	70%	462	38.3	42.2	--	893	0.2245	2.104	1.887	33.6
7	70%	465	60.5	40.3	--	904	0.2210	2.164	1.900	51.7
8	70%	462	102.8	40.4	--	913	0.2210	2.185	1.929	88.6
9	70%	462	101.3	41.7	--	917	0.2235	2.170	1.938	88.4
10	70%	462	200	44.6	--	928	0.2290	2.144	1.968	180.2
1	80%	475	22.2	42.5	--	790	0.2250	1.857	1.643	18.9
2	80%	463	25.0	41.9	--	852	0.2245	2.008	1.791	21.8
3	80%	461	32.0	41.9	--	948	0.2240	2.239	2.002	28.0
4	80%	460	46.5	42.2	--	1009	0.2250	2.372	2.130	40.9
5	80%	461	37.0	43.2	--	983	0.2270	2.291	2.076	32.9
6	80%	464	50.0	40.8	--	1036	0.2222	2.466	2.177	43.0
7	80%	464	86.0	41.2	--	1050	0.2227	2.494	2.210	74.1
8	80%	462	113.8	41.2	--	1054	0.2230	2.500	2.220	98.8
9	80%	461	>200	42.2	--	1065	0.2245	2.510	2.249	175.6

Tested By R. Lamus

Specimen Meets Spec. Requirements Yes ☐ No ☐

Witness ______ Date: ______

Sheet No. ______ of ______

Q. C. Form Approval [signature]

Approved [signature] Date 4/28/69

W 614 A

WYLE LABORATORIES

DATA SHEET

Test Title: CAVITATING VALVE FLOW TEST

Customer: TRW

Part No.: NA

S/N: NA

Spec.: 4715.1.68-43

Para.: N.A.

Job No.: 51393

Date Test Started: 4-2-69

Date Test Completed: 4-4-69

Amb. Temp.: NA

Photo: yes

Test Med.: HYDROGEN

Specimen Temp.: AS NOTED

Specimen: FLOW CONTROL VALVE

* TEST CONDITIONS CORRECTED TO 51.0°R AND 465.0 PSIA

RUN NO	PINTLE POSITION %	INLET PRESS P PSIA	DIFF PRESS ΔP PSID	INLET TEMP T °R	LOW RATE FREQ Hz	HIGH RATE FREQ Hz	SPEC WEIGHT FT³/LB	RATE $\dot{W}$ LB/SEC	$\dot{W}$* LB/SEC	ΔP* PSID
1	100%	462	25.5	43.8	--	1048	0.2275	2.437	2.220	22.8
2	100%	459	35.0	43.7	--	1192	0.2275	2.772	2.534	31.4
3	100%	459	50.5	43.5	--	1295	0.2270	3.018	2.749	45.1
4	100%	462	122.8	41.7	--	1312	0.2235	3.105	2.770	107.1
5	100%	472	109.0	42.1	--	1318	0.2243	3.108	2.751	93.2
6	100%	452	82.5	42.2	--	1305	0.2250	3.068	2.786	74.0
7	100%	459	53.5	42.7	--	1312	0.2260	3.071	2.776	51.8
1	110%	466	10.5	40.2	--	652	0.2210	1.561	1.369	9.0
2	110%	461	20.2	40.0	--	933	0.2208	2.236	1.968	17.4
3	110%	459	25.0	40.0	--	1030	0.2209	2.469	2.178	21.6
4	110%	459	29.0	40.2	--	1113	0.2212	2.662	2.356	25.1
5	110%	462	33.0	40.1	--	1208	0.2210	2.892	2.548	28.4
6	110%	461	42.0	40.1	--	1313	0.2210	3.143	2.769	36.2
7	110%	459	49.0	40.2	--	1370	0.2212	3.276	2.899	42.4
8	110%	456	73.0	40.5	--	1432	0.2218	3.415	3.039	63.9
9	110%	457	97.0	41.2	--	1440	0.2230	3.416	3.054	85.1
10	110%	456	106.5	43.1	--	1442	0.2266	3.367	3.064	95.3

Specimen Meets Spec. Requirements Yes ☐ No ☐

Tested By: R. Lemus

Witness: ____ Date: ____

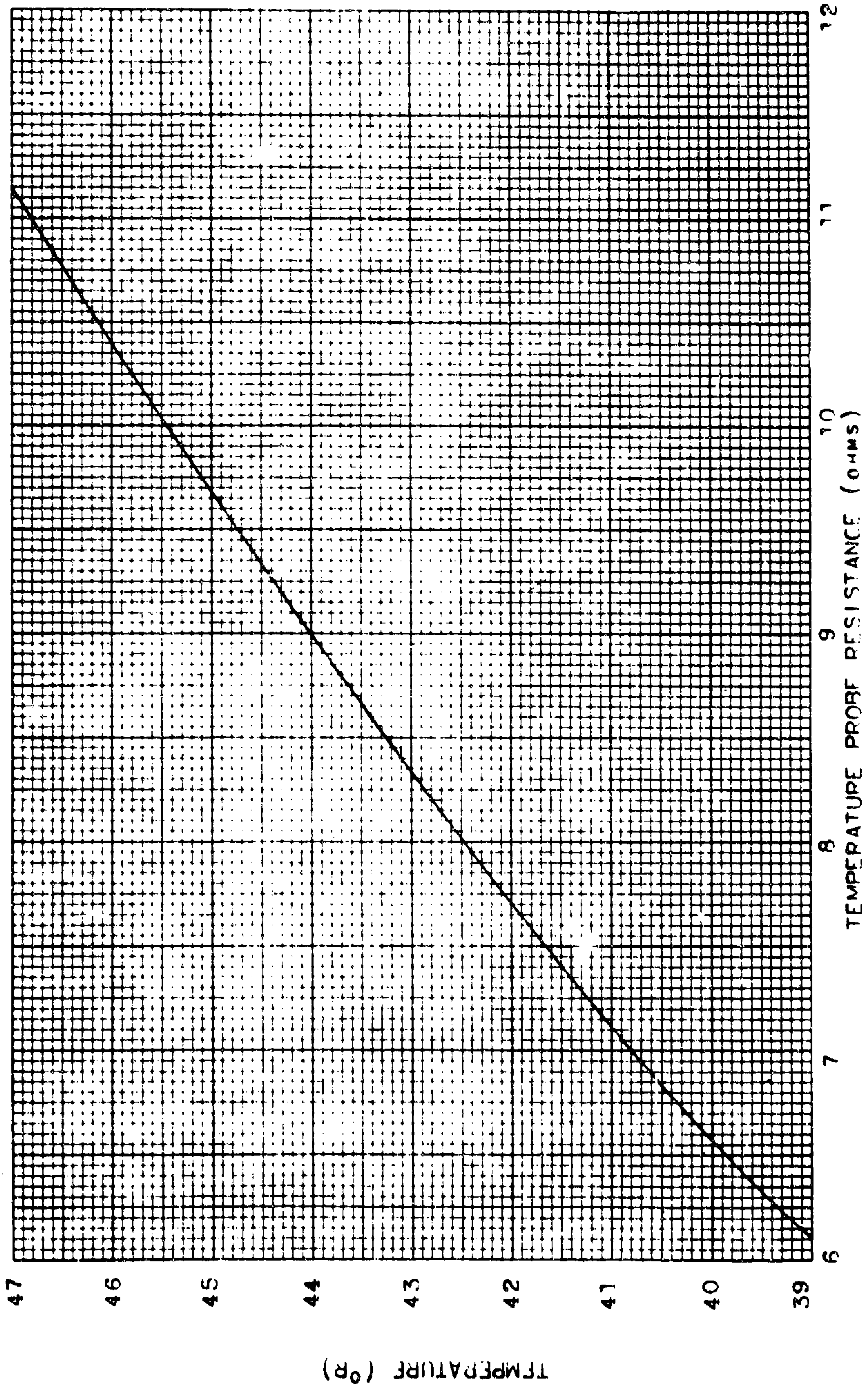
Sheet No ____ of ____

Q. C. Form Approval [illegible]

Approved: [illegible] Date: [illegible]

FIGURE 1

PLATINUM RESISTANCE TEMPERATURE PROBE
ROSEMOUNT MOD. 150MA12



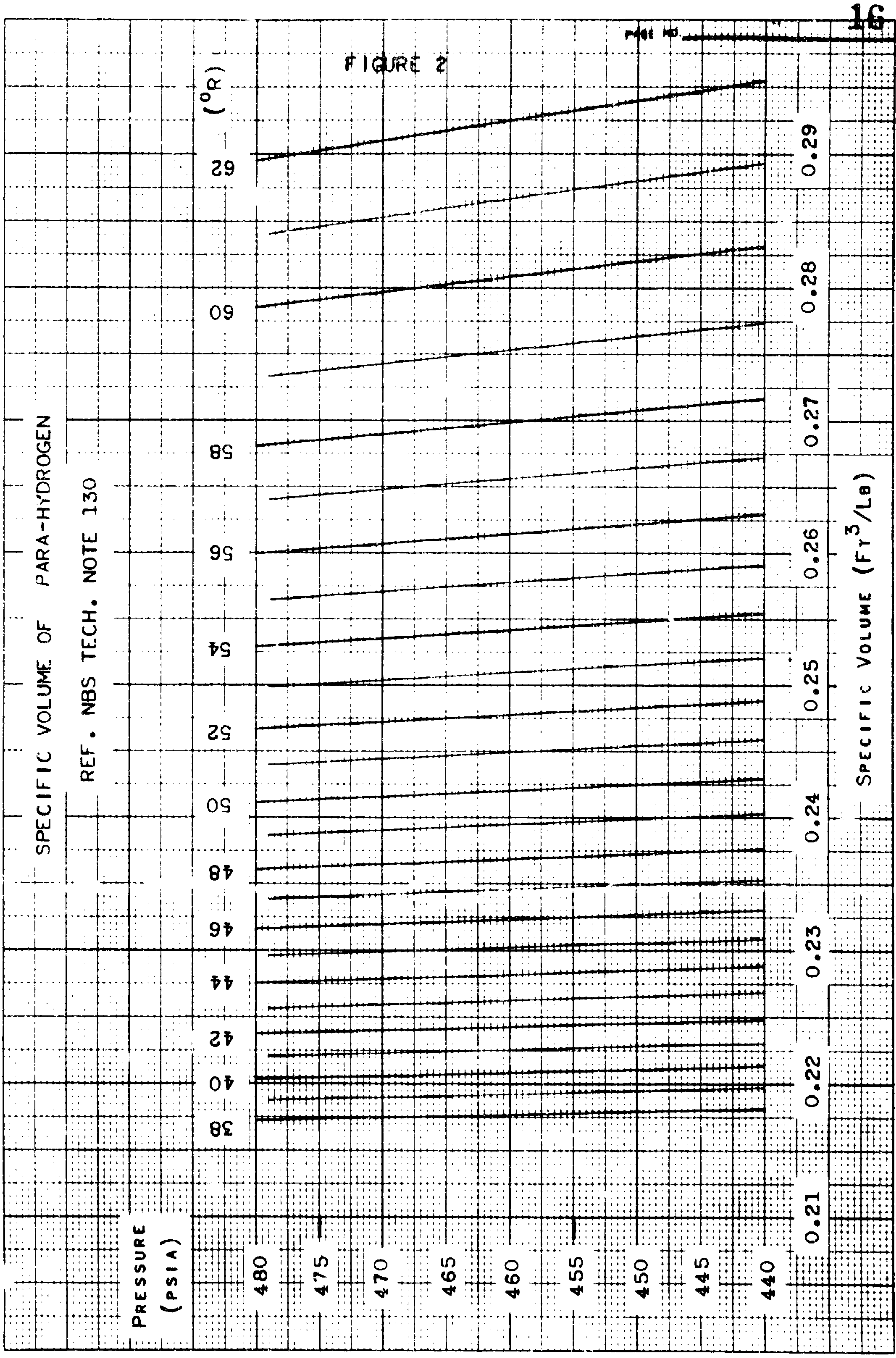
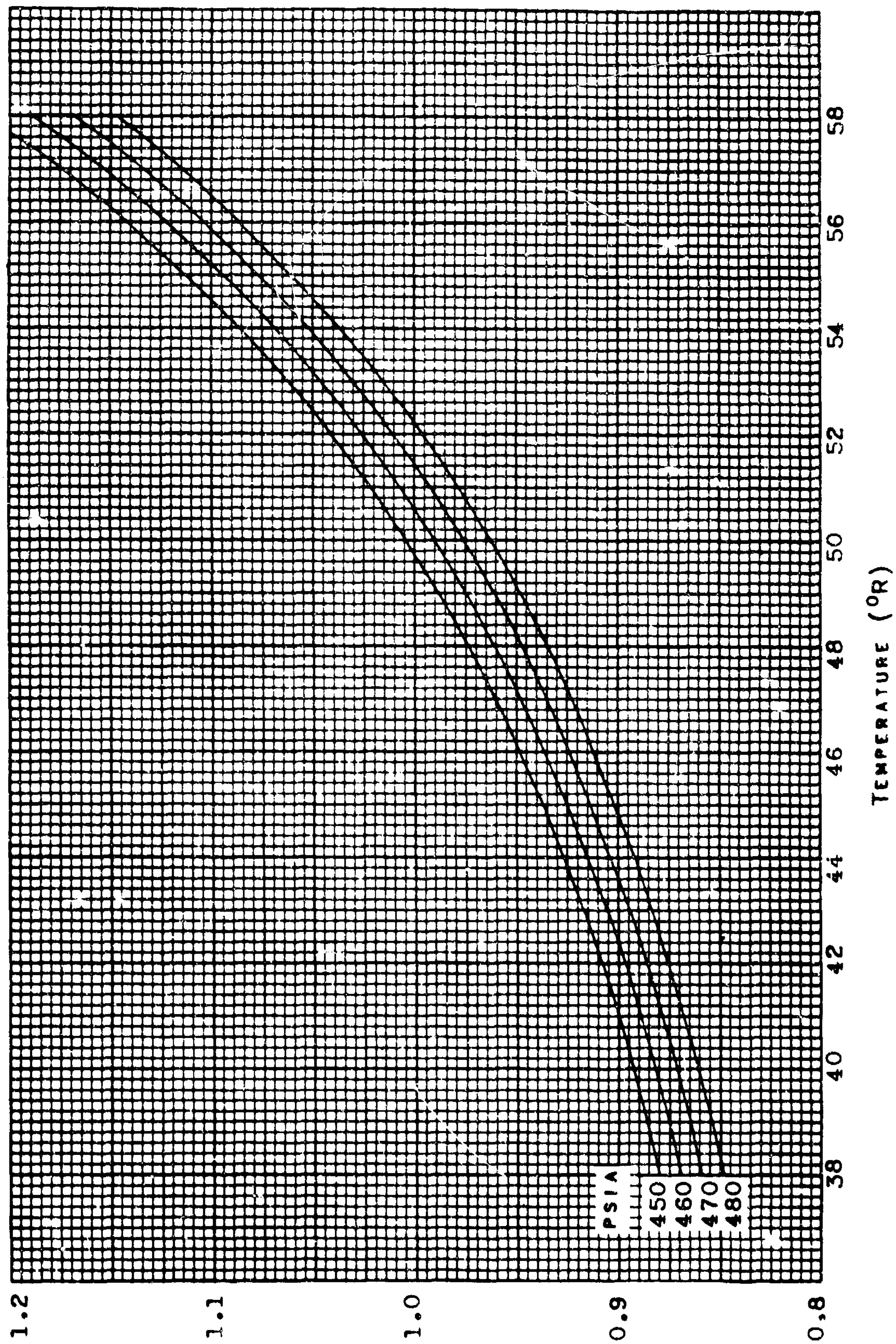


FIGURE 2
SPECIFIC VOLUME OF PARA-HYDROGEN
REF. NBS TECH. NOTE 130
(°R)
62
60
58
56
54
52
50
48
46
44
42
40
38
PRESSURE (PSIA)
480
475
470
465
460
455
450
445
440
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
SPECIFIC VOLUME (FT³/LB)

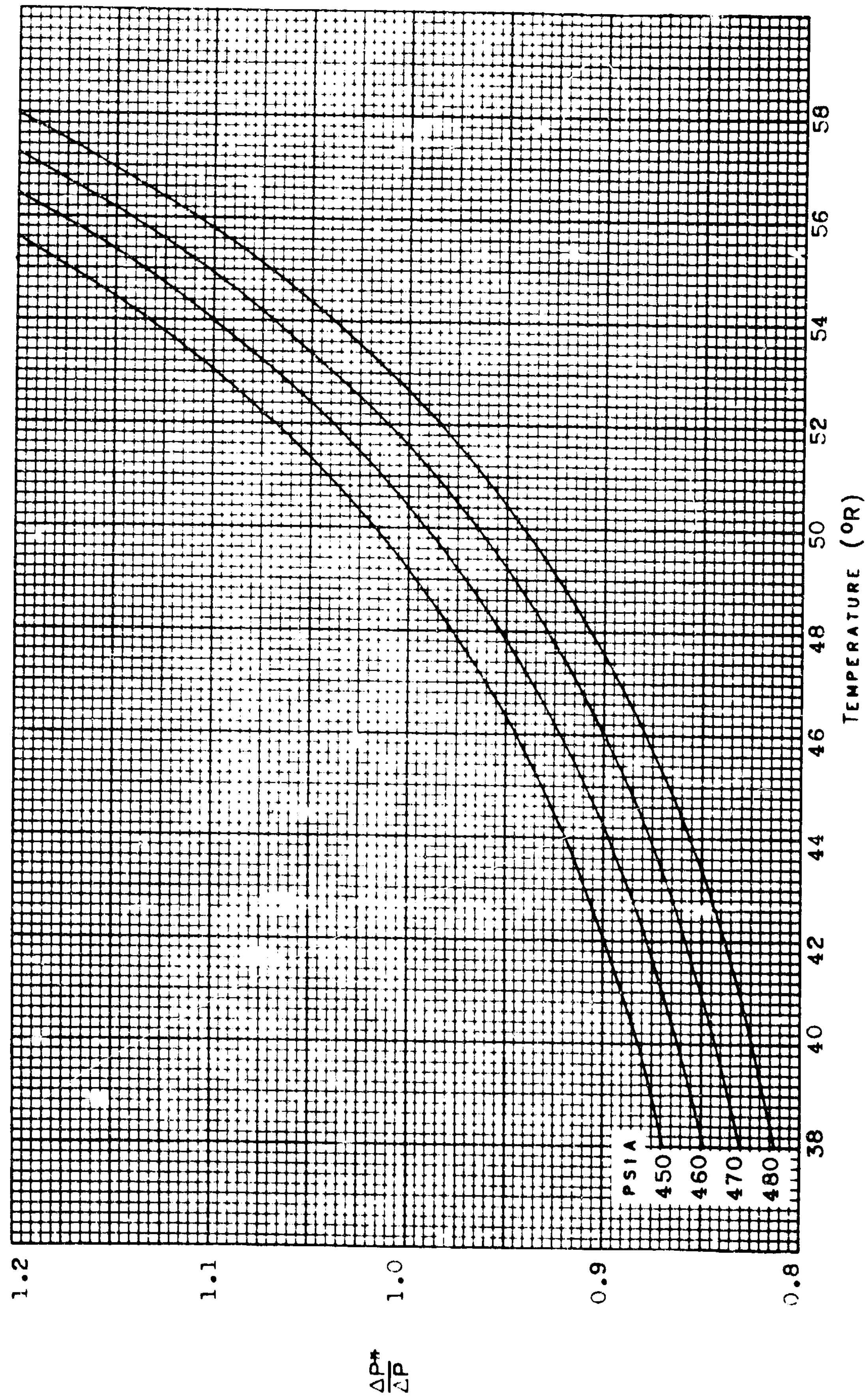
FIGURE 3

CORRECTION OF TEST DATA
TO DESIGN INLET CONDITIONS



#313

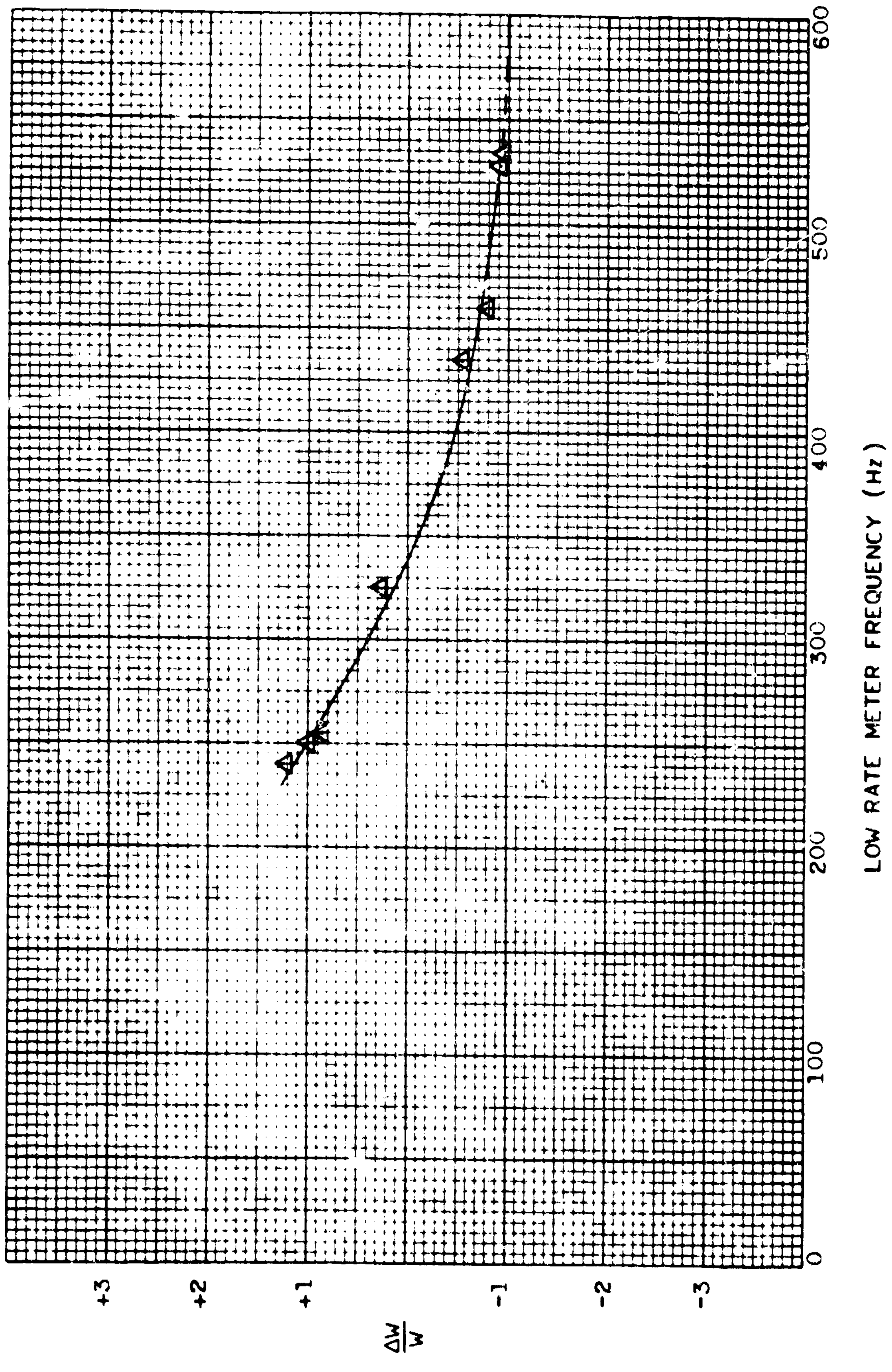
FIGURE 4

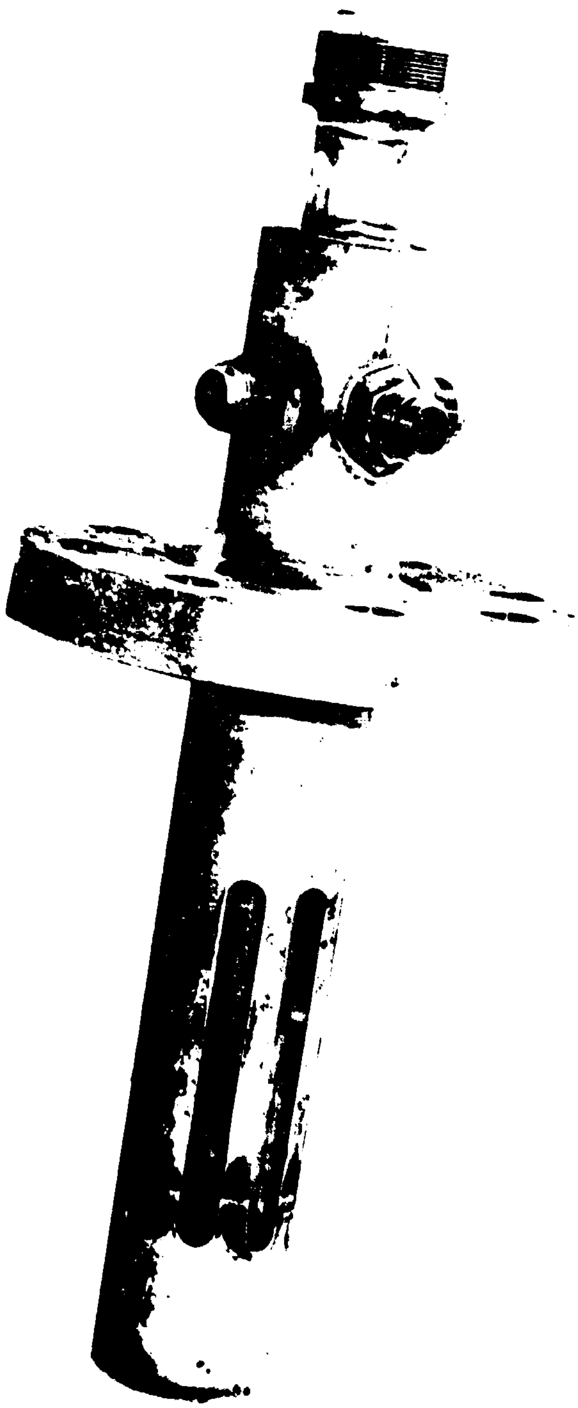


CORRECTION OF TEST DATA
TO DESIGN INLET CONDITIONS

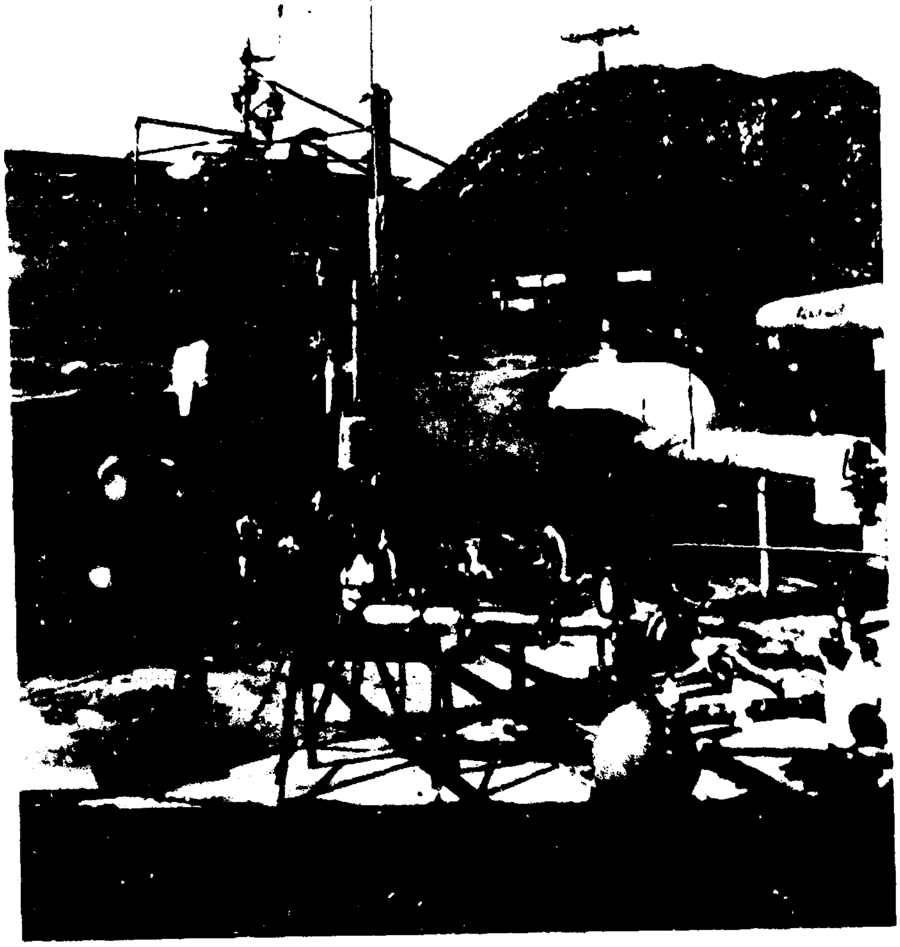
FIGURE 5

DISCREPANCY IN INDICATED FLOW RATE
BETWEEN LOW AND HIGH RATE METERS
IN THEIR OVERLAPPING RANGE





PHOTOGRAPH 1. RUN TANK PRESSURIZATION DIFFUSER



PHOTOGRAPH 4. OVERALL TEST SYSTEM

REPORT NO. 51393

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WYLE LABORATORIES

SPECIMEN: CAVITATING VENTURI VALVE
CUSTOMER: TRW
PART NO: SK 4715-68-147
S N: N/A
TEST: FLOW TEST

JOB NO.: 51393
DATE: 4-3 THRU 4-11-69
TEST BY: H. R. WHEELOCK
WITNESS: N/A

EQUIPMENT	MANUFACTURER	MODEL NO.	RANGE	WYLE NO	CALIBRATION LAST	CALIBRATION DUE	ACCY
RECORDER	MOSELEY	7100B	0-100V	31160	SC *	SC	SC
RECORDER	MOSELEY	7100B	0-100V	31289	SC	SC	SC
RECORDER	MOSELEY	7100B	0-100V	31133	SC	SC	SC
COUNTER	H.P.	5233L	6 DIGIT	31498 **	1-6-69	4-6-69	±1
COUNTER	H.P.	5233L	6 DIGIT	31497 **	1-6-69	4-6-69	±1
CONVERTER	H.P.	500BR	10H → 100KHZ	31524	2-14-69	5-14-69	±2%
OSCILLATOR	HP	200AB	20 → 200X200	30350	1-4-69	4-4-69	±2%
BRIDGE	ROSEMOUNT	400A	35-55R	117	SC	SC	SC
BRIDGE	ROSEMOUNT	400A	90-190R	119	SC	SC	SC
TEMP PROBE	ROSEMOUNT	150MA12	10-500R	7617	SC	SC	SC
TEMP PROBE	ROSEMOUNT	150MA12	10-500R	7618	SC	SC	SC
R. DECADE	E.S.I.	DB52	0-1,111.1Ω	31499	1-20-69	1-20-70	P.S.L.
TRANSDUCER	STATHAM	PL280TC	0-±500PSID	31542	SC	SC	SC
TRANSDUCER	TABER	176	0-1000PSI	30778	SC	SC	SC
TRANSDUCER	TABER	206SA	0-750	623045	SC	SC	SC
GAUGE	MARTIN.D.	B1214	0-1000PSI	31256	3-20-69	4-20-69	±2%
COUNTER	HP	5233L	6 DIGIT	31498	4-6-69	4-14-69	±1

W614C QC Approval [initials]

* SYSTEM CALIBRATION
** RECALIBRATED ON 4-6-69

SHEET 1 OF 2

WYLE LABORATORIES

SPECIMEN: CAVITATING VENTURI VALVE

CUSTOMER: TRW

PART NO: SK 4715-68-147

S/N: N/A

TEST: Flow and ΔP

JOB NO.: 51393

DATE: 4-7-69

TEST BY: H. R. WHEELOCK

WITNESS: N/A

EQUIPMENT	MANUFACTURER	MODEL NO.	RANGE	WYLE NO.	CALIBRATION LAST	CALIBRATION DUE	ACCY.
Gauge	Duragauge	81214	0-1000	30187	3-18-69	4-20-69	±0.5%
Gauge	Ashcroft	2245	0-3000	30755	3-15-69	4-20-69	±0.25%
Gauge	Hoptic/Bourdon	81214	0-1000	31256	3-20-69	4-20-69	±0.25%
Gauge	Duragauge	2149	0-600	31055	3-15-69	4-25-69	±0.5%
Gauge	Ashcroft	AMP 7335	0-15	30963	3-15-69	4-20-69	±0.25%
Gauge	Maxishaft	480	0-16	30232	3-15-69	4-27-69	±0.5%
Counter	H.P.	52336	6 DIGIT	31497	4-6-69	4-14-69	±1

W 614 C Q.C. Approval

SHEET 2 OF 2

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SPECIMEN PINTLE POSITIONING

1. Move pintle fully closed (against closed stop).

2. Set dial micrometer to 0.000 inch.

3. Back pintle open 0.082 inch (this is the 0% open position).

4. Set dial micrometer to 0.000 inch. All subsequent pintle positions are to be referenced to this position.

% Open	Stroke (inch)
2	0.018
5	0.045
10	0.090
20	0.180
30	0.270
40	0.360
50	0.450
60	0.540
70	0.630
80	0.720
100	0.900
110	0.390

REFERENCES

1. F. L. Merritt, L. B. Dumont, et al., "Wide Range Flow Control Program," Technical Report AFRPL-TR-68-32, December 1968, TRW Systems Group, Redondo Beach, California

2. L. B. Dumont, et al., "Development of Cavitating Venturi Valves for Deep Throttling of Cryogenic Liquids," Technical Report AFRPL-TR-65-130, July 1965, TRW Systems Group, Redondo Beach, California

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
This report supplements the final report AFRPL-TR-68-32 dated December 1968.	Air Force Rocket Propulsion Laboratory

13. ABSTRACT The objective of the Wide Range Flow Control Program was to establish propellant flow control valve technology including techniques for mixture ratio control for deep throttling of liquid fluorine-liquid hydrogen rocket engine systems for rated thrust levels between 15 and 45K. The effort described in this supplemental report met the specific objective of proving the technique of controlling the flow of liquid hydrogen by means of a cavitating venturi control valve. Typical inlet conditions for the hydrogen during the tests were a pressure of 405 $\pm$ 10 psia and a temperature of 40° to 45°R. The design mass flow rate at the 100 percent throttle setting was 2.88 lb/sec. Although the hydrogen flow stream was at a supercritical pressure it was demonstrated to act as a subcritical cavitating liquid at the low static pressures prevailing in the valve throat. The feasibility of control was demonstrated over a flow range in excess of 50 to 1 with valve overall differential pressures from 20 to 400 psid. A recovery of 92 percent on the cavitation line at full throttle position was observed. A discharge coefficient of 0.9 from 2 to 10 percent and 0.875 from 20 percent through 110 percent was calculated from the data.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Cavitation						
Cryogenics						
Control, Mixture Ratio						
Flow Analysis						
Flow Forces						
Valve Throttling Range						
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